TESIS DOCTORAL
2020

Strategies of development and maintenance in supervision, control, synchronization, data acquisition and processing in light sources

David Fernández Carreiras

Directores:

José Carlos Dafonte Vázquez
Bernardino Arcay Varela

UNIVERSIDADE DA CORUÑA

Declaración de autoría

Yo, David Fernández Carreiras declaro que la Tesis titulada “Strategies of development and maintenance in supervision, control, synchronization, data acquisition and processing in light sources” y el trabajo presentado en la misma es original.

El doctor José Carlos Dafonte Vázquez, Profesor Titular en el Área de Ciencia de la Computación e Inteligencia Artificial de la Universidade da Coruña, y el doctor Bernardino Arcay Varela , catedrático en el Área de Ciencia de la Computación e Inteligencia Artificial de la Universidade da Coruña hacen constar que la Tesis titulada ”*Strategies of development and maintenance in supervision, control, synchronization, data acquisition and processing in light sources*" ha sido realizada por David Fernández Carreiras, bajo nuestra dirección, en el Departamento de Ciencias de la Computación y Tecnologías de la Información de la Universidade da Coruña y constituye la Tesis que presenta para optar al grado de Doctor en Informática de la Universidade da Coruña.

Firmado: David Fernández Carreiras

Firmado: José Carlos Dafonte Vázquez

Firmado: Bernardino Arcay Varela

ACKNOWLEDGMENTS

The design, installation and operation of the supervision control and data acquisition systems, is a complex endeavor requiring a number of engineers working in collaborations between different institutes. This work studies different cases in particular at ALBA, and the ESRF, the institutes where I got most of my experience across the last twenty years.
I would like to thank all people I had the opportunity to work with. In particular, I would like to thank Jörg Klora, head of the Beamline Instrumentation Software Support group at the ESRF until 2004 and head of the Computing and Controls division at ALBA until 2013. His help, trust, mentoring and knowledge of the field of control systems, detectors and experimental stations have been decisive for my professional development and for the success of projects like Sardana[1:1]. I would like to thank also all members of the Beamline Instrumentation Software Support group at the ESRF and the Computing division at ALBA, with a particular emphasis on Controls and Electronics sections. Among these, I would like to highlight: Alejandro Homs, for his wisdom and advises on a wide field and in particular for his extraordinary generosity, Manuel Pérez and Vicente Rey for their continuous support from the personal and professional points of view, Darren Spruce, Andy Götz, Tiago Coutinho (Sardana, Taurus), Guifré Cuní (Motion Control, Sardana), Sergi Rubio (archiving, alarm handling), Zbigniew Reszela (Sardana and continuous *scans*), Carlos Pascual (Taurus), Fulvio Becheri, Alberto Rubio, Jairo Moldes (Fast Orbit Feedback), Sergi Blanch and Oscar Matilla (Electronics, timing and detectors, besides many other subjects).
I would like also to thank Salvador Ferrer and Dieter Einfeld, heads of the Experiments and Accelerators divisions during the construction of ALBA, for their constant feedback and day-to-day interactions, inputs and advises. Gastón García and Alejandro Sánchez as project managers and with coordination and quality assurance roles during the construction, Joan Bordas and Caterina Biscari, directors of ALBA in the different phases of the project and Ramon Pascual, the President of the Consortium.

I would also like to thank the controls groups of other synchrotrons such as MAXIV in Sweden, PetraIII at DESY in Germany, Diamond in the U.K., Elettra in Italy, Soleil in France and Australian Synchrotron for the exchange of experiences in the past years.
Finally, I would also like to express my gratitude to José Carlos Dafonte and Bernardino Arcay with whom I started to collaborate more than twenty years ago, to work with me in this challenging undertaking.

Resumo

Os aceleradores de partículas e fontes de luz sincrotrón, evolucionan constantemente para estar na vangarda da tecnoloxía, levando os límites cada vez mais lonxe para explorar novos dominios e universos. Os sistemas de control son unha parte crucial desas instalacións científicas e buscan logra-la flexibilidade de manobra para poder facer experimentos moi variados, con configuracións diferentes que engloban moitos tipos de detectores, procedementos, mostras a estudar e contornas.

As propostas de experimento son cada vez máis ambiciosas e van sempre un paso por diante do establecido. Precísanse detectores cada volta máis rápidos e eficientes, con máis ancho de banda e con máis resolución. Tamén é importante a operación simultánea de varios detectores tanto escalares como mono ou bidimensionáis, con mecanismos de sincronización de precisión que integren as singularidades de cada un.

Este traballo estuda as solucións existentes no campo dos sistemas de control e adquisición de datos nos aceleradores de partículas e fontes de luz e raios X, ó tempo que explora novos requisitos e retos no que respecta á sincronización e velocidade de adquisición de datos para novos experimentos, a optimización do deseño, soporte, xestión de servizos e custos de operación. Tamén se estudan diferentes solucións adaptadas a cada contorna.

RESUMEN

Los aceleradores de partículas y fuentes de luz sincrotrón, evolucionan constantemente para estar en la vanguardia de la tecnología, y poder explorar nuevos dominios. Los sistemas de control son una parte fundamental de esas instalaciones científicas y buscan lograr la máxima flexibilidad para poder llevar a cabo experimentos más variados, con configuraciones diferentes que engloban varios tipos de detectores, procedimientos, muestras a estudiar y entornos.

Los experimentos se proponen cada vez más ambiciosos y en ocasiones más allá de los límites establecidos. Se necesitan detectores cada vez más rápidos y eficientes, con más resolución y ancho de banda, que puedan sincronizarse simultáneamente con otros detectores tanto escalares como mono y bidimensionales, integrando las singularidades de cada uno y homogeneizando la adquisición de datos.

Este trabajo estudia los sistemas de control y adquisición de datos de aceleradores de partículas y fuentes de luz y rayos X, y explora nuevos requisitos y retos en lo que respecta a la sincronización y velocidad de adquisición de datos, optimización y costo-eficiencia en el diseño, operación soporte, mantenimiento y gestión de servicios. También se estudian diferentes soluciones adaptadas a cada entorno.

ABSTRACT

Particle accelerators and photon sources are constantly evolving, attaining the cutting-edge technologies to push the limits forward and explore new domains. The control systems are a crucial part of these installations and are required to provide flexible solutions to the new challenging experiments, with different kinds of detectors, setups, sample environments and procedures.

Experiment proposals are more and more ambitious at each call and go often a step beyond the capabilities of the instrumentation. Detectors shall be faster, with higher efficiency, more resolution, more bandwidth and able to synchronize with other detectors of all kinds; scalars, one or two-dimensional, taking into account their singularities and homogenizing the data acquisition.

This work examines the control and data acquisition systems for particle accelerators and X-ray / light sources and explores new requirements and challenges regarding synchronization and data acquisition bandwidth, optimization and cost-efficiency in the design / operation / support. It also studies different solutions depending on the environment.

PROLOGUE

The particle accelerators and photon sources are constantly evolving, attaining the cutting-edge technologies to push the limits forward and explore new domains. The control systems are a crucial part of these installations and are required to give solutions for the new challenging requirements. One of the essential undertakings is reaching the flexibility that allows making experiments very different from each other involving numerous types of setups, detectors, sample environments, and procedures.

The data acquisition techniques have remarkably fast evolved and progressed in the last years. However, the proposals for experiments are more ambitious at each call and go often a step forward from the instrumentation available. The detectors shall be faster and more efficient, with higher bandwidth and resolution, which require a more accurate synchronization with other detectors of all kinds; scalars, one or two-dimensional, different energies, resolutions, spectroscopy, etc. The acquisition is often combined with complex motion trajectories of one or several motorized elements and with specific control of the sample environments. The control and data acquisition systems need to integrate this complexity for managing appropriately the data collection. The data formats must also handle this difficulty and foresee metadata for the corresponding data reduction and data analysis.

The return of investment to the society is an important factor that tackles a very tight budget control in terms of construction, installation and operation. The number of large installations is growing fast but with restrictions in budgets and an increasing competition with other facilities, which empowers imperative efforts improving the efficiency, and reducing the operational and maintenance costs.

This work assesses the new requirements and challenges in terms of performance, design, support and maintenance costs, and studies solutions adapted to the different environments.

Nowadays research and innovation are critical success factors for the progress of the society. Most industrialized countries build and operate large scientific installations of all kinds such as telescopes, particle accelerators, laser, neutron and light sources, etc.
Occasionally, projects are such ambitious that require the collaboration and participation of several countries. Good examples are the well-known, European Synchrotron ESRF[1], or large worldwide scientific collaborations such as CERN[2] and ITER[3].

[1] ESRF: *European Synchrotron Radiation Facility*. The 6 GeV European synchrotron and one of the three largest in the world.
[2] CERN: *Conseil Européen pour la Recherche Nucléaire*. Largest high energy physics laboratory in the world. It is nowadays funded by an international worldwide collaboration.
[3] ITER. International Project to build nuclear fusion reactor at Cadarache (France). It will be the largest tokamak (toroidal chamber for magnetic field plasma confinement) in the world.

Projects used to be so new and specific that scientific installations have often gone for the development of ad-hoc hardware and software for each project. Nowadays this is no longer the case. Today, projects require more and more a high level of standardization with a wide range of products off-the-shelf in order to bring construction and maintenance costs down. Methodologies and standardization of project and service management have proven to be essential for an efficient and competitive construction and operation.

Beamlines and experimental stations in Synchrotrons are constantly growing in number and evolving in capabilities. This is not only the case in the United States, Europe and Japan as it has been for the last decades, but also China, Taiwan, Korea, India, Brazil, are investing many resources in the field. In the last years, China increased spectacularly the investment in research and development projects, counting today with two synchrotrons and a neutron spallation source in operation and an XFEL[4] in construction.

In this environment, the number of Beamlines with similar characteristics and devoted to the same technique is increasing, and consequently the competition for the best users and the best experiments is increasing as well. The progress in data acquisition systems, speed, synchronization capabilities, data processing pipelines etc. is crucial in the strategy for attracting the best scientists and experiments and therefore guaranteeing a high impact of publications and scientific yield.

The supervision, control and data acquisition systems are a crucial part in these scientific installations, engaged to provide solutions to the new challenges and new requirements of the society. One of these challenges, in the particular field of the light sources, is to provide the required flexibility to carry out different types of experiments in diverse fields demanding complex synchronization of various motorized axes, different combination of detectors and sample environments.

Data acquisition techniques experienced a significant evolution in the past years. The experimental proposals are more and more ambitious meaning a step forward in the capabilities of instruments and setups. Detectors are required to go faster, with more resolution and higher efficiency, operated synchronously with other detectors and diagnostics instruments. Data acquisition requires the synchronization of complex trajectories of different motorized axes and different configurations of the environment of the samples, such as furnaces, cryostats, high-pressure cells. Hence, the data acquisition and control systems shall manage this complexity and the data formats shall gather data and all relevant and normalized associated metadata for the latter data processing and scientific data analysis.

---

[4] XFEL: *X-Ray Free Electron Laser*. An installation including a linear particle accelerator (often electrons) combined with long insertion devices (undulators) to produce very bright and short light pulses (X-rays, ultraviolet, visible, infrared). https://en.wikipedia.org/wiki/Free-electron_laser

This work analyzes the existing solutions in the field of supervision control and data acquisition systems (SCADA[5]) for particle accelerators and synchrotron light sources. It evaluates the new requirements, challenges and solutions regarding the user experience, motion and detectors systems, data acquisition speed and synchronization, data management workflows and metadata. It also investigates unsolved problems and challenges, free and open source data policies applied to data, software and science in general[6]. Finally, it evaluates the design and management of services, the project management standards, and the continual improvement approaches for processes and services in the environment of public funded scientific installations.

This work has been accomplished mostly within the previous doctoral plans of the university. It expands from 2010 and due to his own life experience, the author gathers data and experiences collected since 1996 at the ESRF and ALBA[7], although referring also to other large installations such as CERN and SLS in Switzerland, DESY[8] in Germany, MAXIV[9] in Sweden, Solaris in Poland, Soleil[10] in France or Diamond[11] in the United Kingdom. Some institutes apply specific intellectual property policies[12], and consequently documents and data covered by these policies that are not used in this work.

There is a large literature of books and articles written on the control and data acquisition systems subject. In fact, the domain is reviewed by a significant number of magazines such as Transactions on Automatic Control or IEEE Transactions on Nuclear Plasma Sciences Society among others, and like the two above mentioned, published by the Institute of Electrical and Electronics Engineers (IEEE).

In the late eighties, the control and data acquisition systems in large scientific installations got the attention of managers and engineers as a key success factor for the scientific production. Subsequently a number of conferences and workshops are organized as a space to share ideas between institutes and more importantly to create synergies and establish collaborations between individuals, groups and institutes and consequently improve the performance, the

---

[5] SCADA. *Supervision Control and Data Acquisition*. Integrated human machine interfaces and data acquisition and monitoring systems. It provides tools such as data archives, trend charts, alarm handling, recipes, etc.

[6] Open Science: Movement to make publications, data and science in general open and free of charge for the society (https://en.wikipedia.org/wiki/Open_science).

[7] ALBA Synchrotron. Cerdanyola del Vallès, Barcelona, Spain. http://www.cells.es/en

[8] Petra III, DESY, Hamburg, Germany. http://photon-science.desy.de

[9] MAXIV, Lund, Sweden. https://www.maxiv.lu.se/

[10] Synchrotron Soleil. Paris, France. http://www.synchrotron-soleil.fr

[11] Diamond Light Source. Oxford, U.K. http://www.diamond.ac.uk/Home.html

[12] For example, most technical documents at ITER are for internal use only. https://www.iter.org/intellectualproperty

efficiency and reduce the costs. Examples are ICALEPCS (*International Conference on Accelerator and Large Experimental Physics Control Systems*), which last edition was held in Barcelona, Spain in October 2017, (http://icalepcs2017.org/), PCaPAC (*International Workshop on Personal Computers and Particle Accelerators Controls*), NOBUGS (*New Opportunities for Better User group Software*), among others.

The proceedings of many of these conferences are edited and published by JACoW (*Joint Accelerator Conference Website* http://jacow.org/). JACoW was developed at CERN in the nineties and manages the scientific program, all materials, presentations, articles, posters, the attendance and a large number of other services.

OBJECTIVES

The first objective of this work is to tackle the evolution of the control systems in scientific environments and to depict the state of the art of the instrumentation and data acquisition systems as well as the historical technical debt on the working facilities.

The second objective is to identify and analyze the critical success factors for the control and data acquisition systems from both software and hardware points of view, including instrumentation, electronics and detectors.

The third objective is the optimization of standard solutions for the control and data acquisition systems, to make them flexible enough to cover a wide spectrum of experiments, and configurable to be implemented with different hardware, in different institutes. The domain is huge and it is important to note that a scientific installation like a synchrotron covers various disciplines with specific requirements such as particle accelerators and Beamlines and X-Ray experimental stations, being notably different from each other.

The fourth objective covers the costs and the budget and analyzes the impact of the adoption of maintenance and sustainability strategies on the cost-efficiency of the operation.

The fifth objective relates to data management and the implications of the adoption of open data policies and cloud technologies in the particle accelerators and synchrotron light sources. Experiments are more and more automatized what translates into offering services such as remote access and remote control of the experiment, data access, data processing and analysis at the facility. Although datasets can be made public access in the long term, they are in most cases restricted access, at least during the embargo period, which is another challenge for the discipline of cyber-security.

CONTENTS:

1 INTRODUCTION

The control and data acquisition system of a large scientific installation presents specific requirements. Each institute has invested important efforts to meet these requirements [1:1][1:2][1:3][1:4]. In certain environments, this discipline is referred as CODAC[13]. Other common acronyms are DCS[14] and the aforementioned SCADA.

SCADAs usually refer to systems that monitor, supervise and control an installation, industrial or scientific. They provide human-machine interfaces and hardware automation units, reducing the human intervention and improving the overall throughput. A SCADA has often an associated DCS with a number of remote units, often PLCs[15], interconnected by fieldbuses. SCADAs were originally developed to centralize the monitoring and control of a large number of distributed signals in a factory. PLCs are distributed to handle the process automation and data acquisition from different sources referred to as the "field level". SCADAs offer human-machine interfaces and synoptics, together with a growing number of tools and services such as, alarm handling, historical trends, diagnostics[1:5], configuration management, recipes, etc.

The requirements from industry have often to do with large factories, with a huge number of process variables, control points, and specific data acquisition and processing. However, in many cases these control points and process variables belong to a large number of instances of instruments of the same type. That is the market niche of commercial SCADAs, conceived for industrial plants and oriented to improve the performance and efficiency.

On the contrary, large scientific installations, such as particle accelerators, synchrotrons, spallation sources, tokamaks, etc. include often a number of purpose-specific prototypes that need *ad-hoc* software and hardware[1:5][1:6]. Installations share to some extent requirements and complexity as well, although they all have a number of singularities that in several cases have prevailed and triggered the development of new control and data acquisition system from scratch.

One of the most representative examples of the evolution of technology in CODAC systems is CERN. Many particle accelerators have been built and decommissioned at CERN since it was created in the fifties. Control and data acquisition systems have evolved significantly from the first accelerators with manual knobs and analogic indicators, to the challenging and very large LHC[16] with hundreds of thousands control points distributed across 27 Km in radiation hard environments. CERN combines all strategies from *ad hoc* systems developed from scratch to

[13] CODAC: COntrol and Data Acquisition systems.
[14] DCS: Distributed Control System.
[15] PLC. Programmable Logic Controller. Computer specialized in inputs and outputs and executing loop tasks.
[16] LHC: Large Hadron Collider. https://home.cern/topics/large-hadron-collider

the extensive use of commercial SCADAs[1:5]. Synchrotron light sources are another example of installations with specific needs. They have also particle accelerators although employed not as colliders but to produce synchrotron light[17] used in purpose specific Beamlines and experimental stations to carry out experiments.

Scientific installations, in order to accomplish their mission, need to continuously innovate in fields such as mechanics, detectors, fieldbuses and communications, control and data acquisition systems among others. Besides transcendental discoveries in the domain of particle physics, such as boson families W and Z in the eighties (Nobel prices Carlo Rubbia and Simon Van der Meer)[1:7], CERN has fostered the development of other disciplines such as data reduction algorithms, particle detectors and radiofrequency (Nobel prize Georges Charpak for the multiwire ionization chambers[1:8]), or the “World Wide Web” (Tim Berners-Lee and Robert Cailliau)[18]. This progress requires huge investments in terms of resources, largely justified because these findings and inventions are the basement for further projects. The WWW, including languages and protocols, has been distributed as open source software[19] from the beginning, settling the grounds for most computing systems nowadays[20].

In some cases, the technology transfer is made through existing companies or with the creation of new *spin-off* from public scientific institutions, for example DECTRIS[21], created as a *spin-off* of the Swiss Light Source (SLS[22]), and today (2019) market leader in X-Ray Pixel Array Detectors for synchrotrons.

The concept of control systems can be consider from different perspectives. A control system in the field of particle accelerators and in particular of synchrotrons refers to a wide concept of CODAC (Control and Data Acquisition) that includes the design and development of hardware and software, monitoring of process variables, execution of commands, set-points, recipes, macros and sequences, experimental data acquisition and occasionally the pre-process and data analysis.

The chapter 2 analyzes the trends, common tools and international collaborations on the development of supervision, control and data acquisition software, exploring the current state and success factors as well as the origins and the challenges for the future.

---

[17] Synchrotron light: Electromagnetic radiation generated by charged particles moving at near speed of light in a curved trajectory in presence of a magnetic field (Wikipedia). This is covered in chapter 3.

[18] The birth of the WEB. http://home.web.cern.ch/topics/birth-web

[19] The first license is from 1993. These years are also at the origin of open *source* and General Public Licenses (GPL). GPL version 1 is from 1989 and version 2 from 1991.

[20] Initial requirements of WWW: http://www.w3.org/History/1989/proposal-msw.html

[21] Dectris Ltd. https://www.dectris.com/

[22] Swiss Light Source (SLS) at the Paul Scherrer Institut: http://www.psi.ch/sls/

The chapter 3 introduces the basic concepts of particle accelerators and in particular synchrotrons, main focus of this work. This chapter analyzes the environment and the context of the problems to resolve and foresees challenges while depicts a few domains where to focus future efforts. The concepts defined here will be constantly used in further chapters.

The chapter 4 explores the discipline of the control and data acquisition systems from its inception across the evolution of instruments, technology, processors, networks, communications, software models and programming languages. It makes a particular emphasis on the requirements and the solutions implemented during the construction of ALBA synchrotron and their further impact on the project and on the international community.

Detectors and related data acquisition are covered in chapter 5. This is a very specific field highly dependent on the laboratory and on the types of experiments and which is not tackled by commercial SCADAs. Synchrotrons have very specific requirements and although the working basics can be also shared with other domains such as high energy physics, the detectors design for synchrotrons can be considered a different market. The chapter reviews the different types of detectors, their working principles, requirements, their evolution and challenges and the integration in control and data acquisition systems. Each experiment requires a certain detector or in many cases a synchronization of different detectors, with data acquisition rates reaching already orders of magnitude of a few GBytes/sec.

The chapter 6 describes the operation and the maintenance of the installation, focusing on the service and project management. It evaluates the adoption of methodologies and standards such as ITIL best practices at the level of service management or PRINCE2 for project management, combined with agile methodologies such as SCRUM. PRINCE2 and SCRUM present different perspectives for project management in software development. Both have pros and cons for the different types of projects but they can be successfully tailored according to the size and needs, and they can be effectively combined to improve the results.

The chapter 7 analyzes the cyber-security in the field of control systems, which has been traditionally isolated from the outside world and therefore often restricted to physical access. This has completely changed since a few years ago, when cyber-security became, as in many other IT disciplines, one of the most critical strategic requirements of control systems at large scientific installations. Nowadays, cyber-security has a high impact in the design and operation of control and data acquisition systems.

The chapter 8 covers the financial aspects of the installation and studies the cost-effectiveness depending on the required performance and available budget.

Finally, the chapter 9 covers the data analysis, the strategic importance and the future challenges.

1.1 References

[1:1] T. Coutinho, G. Cuní, D. Fernández-Carreiras, J. Klora, C. Pascual-Izarra, Z. Reszela, R. Suñé, A. Homs, E. Taurel, V. Rey. “Sardana, the software for building SCADAS in scientific environments”. Proceedings of ICALEPCS 2011 (p. 607). Grenoble, France.

[1:2] J. Hill, "Channel Access: A Software Bus for the LAACS," in Proceedings of ICALEPCS, Vancouver, British Columbia, Canada, 1989, pp. 352-355.

[1:3] L. Dalesio, M. Kraimer, S. Lewis. D. Murray, W. Watson, M. Clausen, J. Dalesio, “The experimental physics and industrial control system architecture. past, present and future”. Nuclear instruments and methods in physics research, 352(1):179-184. 1994.

[1:4] J-M. Chaize, A. Götz, W-D. Klotz, J. Meyer, M. Perez, E. Taurel, “Tango. An object oriented control system based on CORBA”. Proceedings of ICALEPCS 1999, Trieste, Italy.

[1:5] A. Daneels, W. Salter, “Selection and evaluation of commercial SCADA systems for the controls of the CERN LHC Experiments”, Proceedings of ICALEPCS 1999, Trieste, Italy.

[1:6] A. Marqueta, J. Knaster, K. Nishiyama, A. Ibarra, A. Vergara-Fernández, A. Wallander, M. Zerlauth. “The control architecture of large scientific facilities: ITER and LHC lessons for IFMIF”. Proceedings of ICALEPCS2013. San Francisco CA. USA.

[1:7] C. Rubbia, “Experimental Observation of the Intermediate vector bosons W^+ W^- and Z^0, Nobel Lecture, 8 December 1984.

[1:8] G. Charpak, R. Bouclier, T. Bressani, J. Favier and C. Zupancic, “The use of multiwire proportional counters to select and localize charged particles“, Nucl. Instr. and Meth. 62 (1968) 262.

2 CONTROL SYSTEM TECHNOLOGY IN SCIENTIFIC INSTALLATIONS. COMMERCIAL SYSTEMS AND INTERNATIONAL COLLABORATIONS

Automation, control and data acquisition systems were initially developed to replace a manual process that required human intervention with an automatic process, faster, cheaper and more efficient. In scientific environments, the evolution came from the development of new devices for new experiments, more focused on the functionality and less on the cost. Industrial systems on the contrary, are always more concerned about the efficiency in terms of operational and maintenance costs, and consequently experienced a more homogeneous evolution, while the scientific installations were driven more by ad-hoc solutions in terms of instrumentation and software for a particular problem in a particular situation.

2.1 Control systems architecture: Distributed control systems

Control systems are distributed and rely on communication between different pieces of hardware since the decade of 1970. The first distributed systems incorporated serial protocols like RS-232[23] and other standards like CAMAC[24], Ethernet[25], AppleTalk[26], RPC[27] etc. Actually, the final systems were a combination of many of these. Already at that time, particle accelerators were increasingly larger incorporating a huge number of signals up to ranges of 100.000 [2:1]. The control system for the pre-injector of the LEP[28] at CERN [2:2] was designed in the early eighties and was representative of the paradigm change to distributed systems from the IBM T1800 mainframes, widely used for control and data acquisition systems at the time. Communication networks and fieldbuses revealed their great potential in terms of scalability, reliability and flexibility. The architecture of the control systems became a key aspect related with the overall performance of the laboratory.
Fielding [2:3] defines a set of properties characteristics of the architecture.

- *Performance*, can be seen as the speed of communications, efficiency of fieldbuses data networks, perceived latencies... It has also to do with optimization of the amount of data to be transmitted and consequently the speed perceived by the user.

---

[23] RS-232, RS-422 (differential), RS485 (multipoint support)… RS stands for Recommended Standard. RS-232 was introduced in the 1960 as protocols to interconnect DTEs (Data Terminal Equipment) with DCEs (Data Communication Equipment).

[24] CAMAC: *Computer Automated Measurement And Control*. Standard chassis for data acquisition cards used in industry and scientific installations. Popular in the eighties. Today obsolete and discontinued.

[25] Ethernet. Network technology extensively used in Local Area Networks (LANs). Their use took off in the eighties with the protocol CSMA/CD (Carrier Sense Multiple Access / Collision Detection). Today it is still the most popular technology although every collision segment is isolated and the modern *switches* no longer allow collisions.

[26] AppleTalk. Network protocols developed by Apple in the eighties. Today they are obsolete and discontinued.

[27] RPC. *Remote Procedure Call.* Communication infrastructure for distributed systems.

[28] LEP. *Large Electron Positron Collider*. Electron-Positron collider 27 Km long that started operation in 1989 and was decommissioned in 2000 to start the installation of LHC in the same tunnel.

- *Modifiability*, described as the capacity to be extended and accept changes. Requirements are never frozen and in particular those of control systems constantly evolve to bring solutions to further needs.
- *Reliability*, fault tolerance and facility to isolate and identify failures, and to resolve problems.
    - *Reliable and redundant designs can be conceived as fault tolerant in configurations of high availability or fail safe in configurations of protection systems (for example, the Personnel Safety System or PSS).*

It is important to highlight the property not considered in the early days that became crucial in the current systems: the cyber-security. Distribution and communications bring value to control systems, increase service levels, reliability and performance, but at the expenses of introducing new risks in terms of integrity and communications security.

2.1 Design and implementation strategies: Ad-hoc approaches versus commercial SCADAS and outsourcing.

When industrial control systems evolved from electrical analog-based signals with potentiometers and cabled logic to digital with an extensive use of computers and PLCs, the SCADA[29] concept took a prominent role. They started offering simple Human Machine Interfaces (HMI[30]), and rapidly evolved incorporating modules for database archives, alarm handling, recipe management, trending charts, historical plots, etc. The PLCs and SCADAs markets adapted rapidly to the distributed control systems and supported various communication networks and fieldbuses, like Siemens H1, L2, etc.

PLCs evolved from centralized architectures with one CPUs with a large number of analogue 0-10V; 4-20 mA and 24V digital input/output cards to decentralized with one CPU with a reduced number of input/outputs communicated through fieldbuses to many remote periphery modules with input/output cards. The communication channels were proprietary fieldbuses in the beginning and later standard Ethernet. These conditions created the environment for the popularization of Distributed control systems Ethernet based[31] [2:4].

[29] SCADA. *Supervisory Control And Data Acquisition*. Software offering human machine interfaces and other tools to monitor and control industrial plants. Traditionally they were natively integrated with PLCs for access to the field.

[30] HMI. *Human Machine Interfaces.* Graphical, text or in general any type of interface between the computers and the humans.

[31] Tanenbaum and Van Renesse identified already distributed systems in the eighties. They provide an abstraction layer to hide the complexity of the physical distribution and make it transparent to the user.

At the same time, PLCs were also used in the research facilities and laboratories, but together with combination of other ad hoc devices and standards such as CAMAC, VME[32], NIM[33] modules, etc. These environments were the state of the art at the end of the eighties. In the nineties, the VME bus was broadly standardized and with the control systems of the newer accelerators playing an important role. Examples are CERN, with the LHC as the most important case and the ESRF. From the nineties, the use of PLCs is widely adopted in scientific installations, notably for subsystems such as cryogenics, vacuum interlocking, machine protection and later for general purpose control systems. In this context, the control systems became a combination of PLCs, VME crates based on Motorola CPUs and real time operating systems (OS9, VxWorks, LynxOS, RTEMS among others).

The control systems naturally became distributed (DCS[34]) but human machine interfaces were heterogeneous, purpose specific, based on different programming languages and technologies.

The scientific installations still may have singularities that impose one particular solution, such as radiation hardness, that was decisive for the adoption of WorldFIP[35] fieldbus at CERN. Table 1 compares the main characteristics of industrial control systems and large scientific installations control systems.

Nineties and years 2000s.	**Industrial control systems**	**Scientific installations control systems**
Access to the field.	PLCs Small number of large PLC-CPUs In the late nineties, the use of remote periphery became more common to facilitate cabling.	Distributed control systems based on data networks and field buses. PLCs, VME, CAMAC, NIM, extensive use of serial lines: RS232, RS422, RS485. Radiation hard fieldbuses like WorldFIP.
Supervision software	SCADA. Commercial software communicating with the PLCs evolved over the nineties with utilities for the interactive	Developed ad hoc. EPICS was popularized in the nineties allowing more reuse of software and tools and reducing

[32] VME: Versa Module Europa Bus. Standard bus developed for Motorola 68000 series.

[33] NIM: Nuclear Instrumentation Module. Standard specifying mechanical and electrical connections for data acquisition card in particular oriented to nuclear facilities and other scientific installations.

[34] DCS: Distributed Control System.

[35] WorldFIP. World Factory Instrumentation Protocol. One of the eight fieldbuses defined in IEC 61158. It https://en.wikipedia.org/wiki/Factory_Instrumentation_Protocol

	creation of synoptics, alarm handling, sequencers, recipes, archiving etc. They are often independent modules with particular licensing.	the costs of development and implementation.
Regulation, feedback and control	PLCs and ad-hoc electronics designs. Application Specific Integrated Circuits (ASICs)	VME, real time operating systems. Ad-hoc electronic designs and PLCs.
Databases support	Modules for historical databases, trending charts, backup of data, etc.	Separated tools developed purpose specific.
Integration with ERPs[36]	NO	NO
"on-line" data processing	Basic. Integrated in PLCs	On purpose design based on the particular applications

Table 1. Comparison between industrial control systems and scientific installations

A recent installation, such as ALBA commissioned between 2011 and 2013, still occasionally may need to use exceptionally VME, NIM and other legacy chassis.

The paradigms aforementioned in Table 1, still valid until the first decade of the XXI century, are rapidly changing in the second decade as shown in Table 2. In 2020 the standards of the industry can be also applied in most cases to distributed control systems in scientific installations, and the principles that had ruled industrial environments are now more flexible. There are reasons for that. The scientific institutes are now more concerned about budget restrictions, installation and maintenance costs and overall efficiency. They use COTS products when possible and reduce the staff for the construction and operation of these systems.

	Large scientific installations control systems: Years 2010´s
Access to the field	Internet of Things. Wireless communications (Wi-Fi[37], Bluetooth[38]). PLCs.

[36] ERP: Enterprise Resource Planning. Software management tool oriented to finances, accounting, human resources, stocks, etc.
[37] WiFi: standard wireless communication protocol implemented on 2.4 and 5 GHz frequencies based on the "Institute of Electrical and Electronics Engineers (IEEE) norm 802.11.
[38] Bluetooth: standard wireless communication optimized for short distances and low power consumption.

Supervision software	SCADA either commercial or custom made. Integration with ERP and business units. Internet connectivity. Remote access.
Regulation, feedback and control	PLCs. Custom made electronics designs. FPGAs
Databases support	Integration with corporate databases. Hardware repositories and configuration management. Integrated service management. Business intelligence tools, big data and machine learning. Incipient use of cloud computing and software as a service (SaaS).
Integration with ERPs	Yes, although under certain assumptions and cyber-security conditions.
"on-line" data processing	Data preprocessing. Configurable *Plugins* for specific applications.

Table 2: Industrial and scientific control systems in 2020.

The current trend is to find sensors with a microcontroller and a communication interface distributed across the facility and communicated through the network, that are more and more wireless. In other words, "*Internet of Things*" (IoT) and cybersecurity are also getting an important attention on the control systems field. The concept is replacing the previous paradigm of simple sensors connected to PLC input/output cards. The level of abstraction remains modular and organized in different layers, each one managing and processing the relevant information to produce the adequate reports as shown in Figure 1.

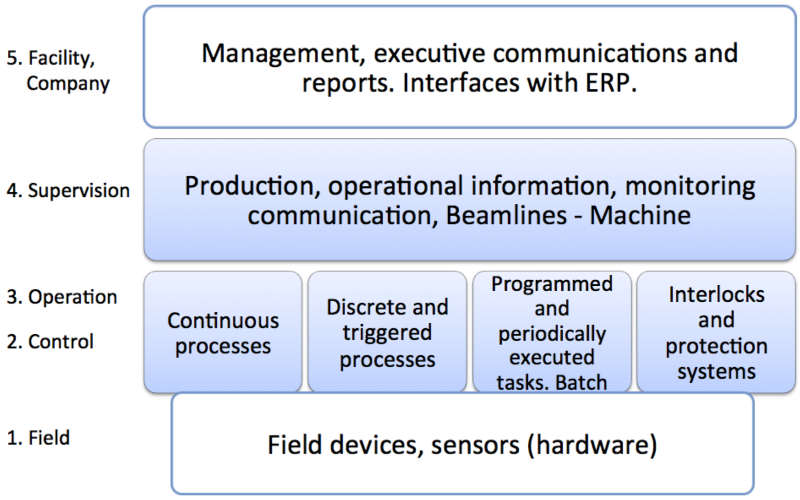


Figure 2-1: Functional topology of a control system [2:5]

2.2 Control systems and international collaborations. EPICS and TANGO

EPICS[39][2:6] and TANGO[40][2:7] are toolkits and frameworks that provide an environment around a communication middle layer to develop distributed control systems. In certain contexts they are known better as "control systems" rather than "software buses".

EPICS was born from an initial collaboration between Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL) both in the United States. The collaboration focused on the construction of the "Advanced Photon Source" (APS) synchrotron in Illinois. This took place in 1990 and since then EPICS became the most used "control system" for scientific installations around the world.

TANGO was born from the evolution of the system developed in the early days of the ESRF: TACO based on RPC. TANGO unlike TACO is based on CORBA[41] and was initially developed at the ESRF in 1999. The ESRF had run on stable operation since 1993 and both Beamlines and Accelerators only used TANGO for a few particular projects. The implementation across Beamlines and accelerators took several years and was fostered by the creation of a collaboration; this happened with the Synchrotron Soleil in Paris, France, in construction at the time, was looking for a solution for the control systems and signed a memorandum of understanding with the ESRF in 2000. In 2004 the synchrotrons Elettra and ALBA joined, followed by DESY and others until reaching more than 30 participants, counting public institutions and private companies[42]. TANGO is the control system more used in scientific installations in Europe whereas EPICS is leader in the world, in particular in America and Asia. Both provide standard tools to build control systems and are available as a free open software in public repositories.

The success of both collaborations relied on their ability to override the "ego" at the different facilities that based on their convictions on the "uniqueness" of their systems, their requirements and their engineers used to make these facilities undertake the development their own systems nearly from scratch.

---

[39] EPICS: "Experimental Physics and Industrial Control System": Framework, libraries and applications to develop distributed control systems for particle accelerators, telescopes and other large scientific installations. http://www.aps.anl.gov/epics/index.php

[40] TANGO: "TAco Next Generation Objects": Open source toolkit for the development of control systems and SCADAs in distributed environments. http://www.tango-controls.org/

[41] CORBA: Common Object Request Broker Architecture. Standard object oriented communication infrastructure to develop distributed software applications

[42] http://www.tango-controls.org/community/institutions/

The extensive use of version control tools and common repositories was and still is the main ingredient to ensure the quality and the organization of the collaborations. Both EPICS and TANGO started with SCCS and later used CVS, SVN to finally evolve to GIT.

Offering tools and not a closed system also contributed to the rational organization of the collaborations, where each of the laboratories could reuse tools and code produced by others or develop their own if required. In these contexts, the user communities provide tools and modules such as *device servers* or *records* following their own terminologies to integrate hardware components. This level of integration is not yet comparable to commercial SCADAs.

On top of these products, other projects have contributed with the integration of graphical user interfaces, command line interfaces and optimization to the hardware and datasets. A meaningful example is Sardana [2:8], based on Python, developed initially at the synchrotron ALBA and turned into a de-facto collaboration between four institutes, MAXIV, DESY, SOLARIS and ALBA, and with tens/hundreds of users across public institutes and private companies.

2.3 Ethernet as the standard fieldbus

Industrial networks combine advantages of fieldbuses and computer networks. They reduce costs and increase the bandwidth. They are extensively used today in the PLC world and industrial applications. Most manufacturers have developed their own network Ethernet based with deterministic capabilities such as ProfiNet[43], EtherCat[44] or PowerLink[45]. The main inconvenient for the installation and maintenance is that in most cases standard hardware is not suitable due to the additional latencies it can introduce. In other words, these industrial networks often require dedicated switches, fiber optics and cables and therefore they do not profit from the monitoring and diagnostic tools of the corporate network.

The design of the fieldbuses and network topologies is tightly linked to the general architecture of the distributed system. PLC based systems, which can handle tens or hundreds of thousands of signals, often require response times in the millisecond range. This is the case for example of protection and interlock systems. The aforementioned deterministic networks properly handle these requirements, although today the common trend is to go one step further and reach nanosecond ranges or better with the Precision Time Protocol (PTP). One notable example is

[43] ProfiNET: Deterministic Ethernet Network. Proprietary SIEMENS.

[44] EtherCat: Open source protocol for the use of Ethernet in industrial environments. The technology was initially developed by Beckhoff

[45] Ethernet PowerLink (EPL). Open source deterministic network protocol originally developed by B&R.

the White Rabbit [2:9] project that introduces deterministic network switches and the combination of star and ring architectures.

The increase of the transmission speed and the decrease of the latency makes possible high precision deterministic systems based on data networks and also opens the possibility of synchronization by software.

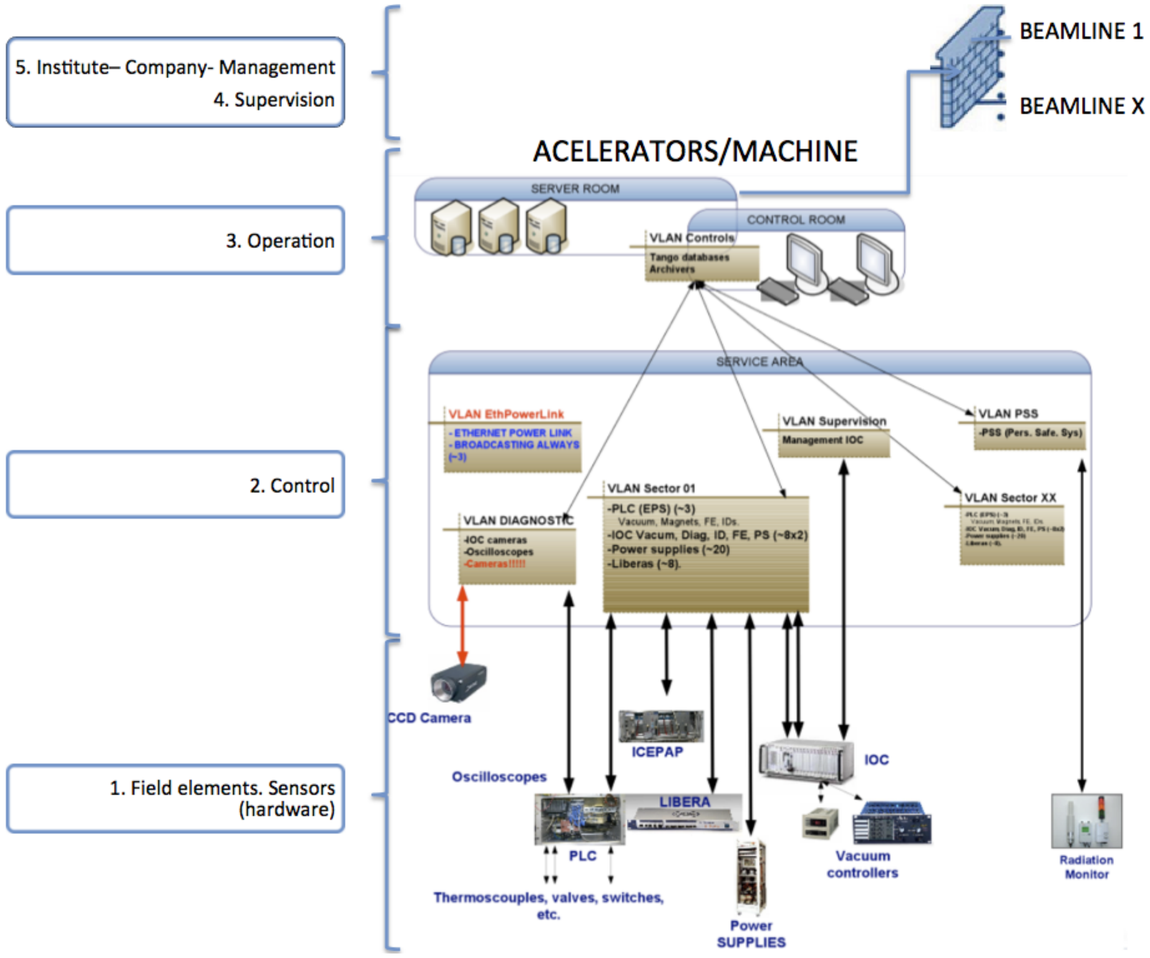


Figure 2-2: Initial draft design of networks and fieldbuses of the particle accelerators at ALBA

Figure 2-2 shows the architecture of the control system at different levels with an extensive use of Ethernet as fieldbus, relying on properly segmented networks separated between data acquisition hardware in the field on one side and configuration and data processing software running on virtual machines in the data center on the other side.

2.4 The election of python as programming language

Python[46] is a programming language with a huge projection in the scientific community. Guido Van Rossum started the project in the nineties and created an interest in many environments among the scientific community. The interest in the project rapidly grew in several fields like scientific environments. The ESRF started using it in the early days. Later, it was adopted by ALBA as standard since the beginning when the project started. The control and data acquisition software at ALBA uses Python in more than 90% (being the rest C++ and Java for legacy components mostly)[2:10]. Python is used for Human Machine Interfaces (combined with Qt[47]), data acquisition programs and data analysis.

The Sardana project started with a core in C++ that later was migrated to Python. The access to the hardware, the data acquisition modules and the sequencer and macro environments are developed in Python. The Taurus[48][2:11] project, developed in Python and Qt, provides graphical tools to interact with the operators, distributed control systems and any data source. Python is intuitive, powerful and has an easy learning curve. Since it is interpreted, is suitable for rapid prototyping and testing. Powerful operators such as *eval* to evaluate arbitrary expressions, modules such as *numpy* for optimized matrix operations, or *regexp* for managing regular expressions are some of the reasons of the suitability for scientific environments. Qt, (and the Python extension PyQt) has a large community and offers a powerful development environment that incorporates features such as the event/signal transmission system very suitable to meet the requirements of graphical applications of the control systems.

Still in 2005 many scientific installations used primarily other programming languages such as Java or C++. Nowadays in 2020, Python is one of the most popular in scientific installations, present in a way or another in all of them. It is the most used to define acquisition macro sequences at the major labs (ESRF, SLS, Elettra, MAXIV, Solaris, Diamond light source etc.). Many research groups use Python for data analysis in any step of the process, combined with other non-commercial and commercial tools such as *Matlab*[49], *Mathematica*[50], *Igor-Pro*[51], etc.

---

[46] Python: An interpreted programming language available for a number of platforms and suitable for a large number of different environments, ranging from content management systems to data analysis programs. (https://www.python.org)

[47] Qt: Framework multiplatform to develop graphical Human-Machine interfaces and manage graphical applications. (https://www.qt.io).

[48] Taurus: www.taurus-scada.org/

[49] Matlab: MATrix LABoratory. Software tool developed initially oriented to mathematical calculus that became the marked leader in the commercial applications market for data analysis software, data acquisition, closed loop systems, modeling, simulation, etc. (https://es.mathworks.com)

[50] Mathematica: Mathematical analysis and calculus software package (https://www.wolfram.com/mathematica).

[51] Igor Pro: Scientific software for data analysis, numerical computation and graphical interfaces (https://www.wavemetrics.com)

2.5 Virtualization, Linux as the preferred operating system and containers

Unlike the industry, where the control systems and SCADAs run mostly on Windows platforms, Linux based distributions are the most popular in scientific environments. When personal computers offered a suitable performance and user experience, automation and industrial control systems started massively using personal computers complemented with PLCs; SCADAs were made available for OS/2[52] and later for Windows95. Microsoft would domain the market with later windows versions 98, 2000, NT, XP, Windows7, 8, 10 until today. In the early nineties Linux was still embryo and Unix installations were mostly based on commercial versions AT&T Unix SystemV. There were different platforms such as Unix based PDP-11 from Digital Equipment Corporation (DEC), later evolved to VAX (Virtual Address Extended PDP-11) running the VMS operating system developed by DEC as an evolution of Unix for their new platform. OpenVMS appeared later as the response to VMS expensive licenses, but it did not gain the critical number of users and was largely dominated by Unix based systems which profited from being open source (e.g. FreeBSD[53] and later Linux[54]), and therefore studied and popular at the universities. Besides, the research and development of the networks, in particular the TCP/IP protocol on the Unix environments, and the success that encountered was crucial as well for the Unix systems.

In parallel to free and open source versions, other vendors fostered their Unix like operating systems with their dominant positions selling hardware. The most significant in the nineties were HP with HP-UX and Sun Microsystems with Solaris. Later they disappeared faced to the success of Linux distributions such as RedHat, CentOS, Suse, Debian and Ubuntu among others. The Linux market is constantly growing with new distributions for new markets like Yocto, for embedded systems.

The trend in the last years shows that the market moving to FOSS[55] [56]. The market leaders in the eighties and nineties either disappeared[57] or adapted to Linux based operating systems. Linux are preferred in Input-Output controllers managing input/output cards, in workstations for human machine interfaces and in virtual machines for processing, configuration and

---

[52] OS/2. Operating system initially created by IBM in collaboration with Microsoft in 1987

[53] FreeBSD: Berkeley Software Distribution. Version developed at Berkeley university https://en.wikipedia.org/wiki/FreeBSD

[54] FreeBSD and Linux cannot compare directly. FreeBSD is a whole operating system whereas Linux refers often only to the kernel.

[55] FOSS: Free and Open Source Software.

[56] The exception is MacOS-X, the Apple operating system for Macintosh with a kernel (Darwin) derived from NEXTSTEP that is as well derived from open source kernels FreeBSD.

[57] DEC was bought by Compaq that was bought later by HP, that later took out the focus on operating systems.

managing central services. Yet these Linux based systems shall coexist with Windows. Windows based systems have always kept the market share in industry and there are instruments that only provide drivers and software for Windows. Therefore, the control systems shall be multiplatform even though in scientific environments Linux run 80%-90% of servers and workstations.

Linux based systems are commonly found as well in network switches, hypervisors for virtual machines and other components of the IT infrastructure.
The virtualization is gaining presence in services and applications. The virtualization can be seen as the virtualization of machines (hardware), applications and desktops. The virtualization of the applications and desktops and in general the software as a service (SaaS[58]) is extensively used since the first decade of the XXI century both in industrial applications and general purpose[59]. The virtualization of applications and desktops is also present in scientific environments, although not yet common in the control and data acquisition system input-output controllers.

However, the hardware virtualization is already predominant in the IT services infrastructure and in the control system general services. There are several hardware virtualizations with different uses:

- Virtualization: The guest operating system runs without being modified nor recompiled in an environment managed by the host operating system or hypervisor that runs on the bare-metal servers. Hardware vendors have adapted to this new paradigm as the number of virtualized services is rapidly growing and as of today they largely dominate the market. Services such as directories (LDAP), domains (DNS), authentication and even occasionally firewalls run in virtual machines. There are nevertheless still a few cases where the virtualization is not recommended, such as with intensive use of input-output, such as network (data acquisition from CCD cameras and detectors with a high bandwidth) or disk (such as certain databases), or any other fast access to the hardware. However, the advantages are so clear, such as backups, disaster recovery, availability, maintenance and ease of hosting.
- Para-virtualization: In some cases, the guest operating system needs an adaptation and recompilation to run on the hypervisor. This is not so common in scientific scenarios.
- Dockers or containers[60]: This is a popular solution because of the ease of use and flexibility. It is not a complete virtualization, but a sort of a virtual environment with dedicated resources, libraries and other components, but sharing the operating system kernel. There are also implementations for Windows, although the discipline is

[58] SaaS: Software as a Service. Provision of software applications without any physical installation on the local machines.
[59] We can name Citrix Xenapp, Vmware ThinApp and Microsoft SoftGrid as most significant SaaS providers.
[60] See Wikipedia: https://es.wikipedia.org/wiki/Virtualizaci%C3%B3n_a_nivel_de_sistema_operativo

dominated by Linux environments. This is extensively used in public and private clouds, test environments, continuous integration and continuous delivery. This technology is rapidly evolving, and currently large docker systems rely on orchestrators such as kubernetes[61], and additional deployment and load balancers tools such as rancher[62].

In summary, the virtualization became critical for the operation of control and data acquisition systems and DevOPS in general. Virtual machines and in particular dockers are crucial for the development of test environments and continuous integration, continuous delivery and deployment.

2.6 Cloud computing.

Distributed computing evolves together with the computer networks [2:12]. In the nineties, the data storage and experimental data analysis required expensive IT infrastructure, such as tapes, disks cabinets and computing clusters on-premises. The LHC project was conceived to produce more than 30 TB/day and required a new paradigm, with data centers organized in a star connected to the center tier-0 (on premises at CERN, continuously updated and recently in a different country). The star shaped infrastructure comprised thirteen Tier-1[63] and more than 150 Tier-2[64]. This network is managed by the international collaboration *Worldwide LHC Computing Grid*. Grid networks are a sort of parallel computing infrastructures built with conventional computers, distributed across different datacenters in the world and interlinked through a high performance network. Computers can be managed by clusters and grouped in queues.

Neutron or photon light sources experienced a notable increment of data production as well. Experimental stations install faster detectors capable of producing GBytes/second added to the automation of data processing make the production of data doubles every 2 or 3 years. Local datacenters and on premises high performance computing clusters[65] are no longer enough to handle such amount of data.

The solutions are either delegating the difficulty to the invited scientists who will end up having the same problem at their home institutes or relying on private clouds, federated and combined with public clouds for handling peak-loads.

---

[61] Kubernetes: Open source container orchestrator for automatic deployment and management. https://en.wikipedia.org/wiki/Kubernetes

[62] Rancher: Complete open source container management multiplatform. https://rancher.com/rancher

[63] There is a Tier-1 in Spain located at the Universitat Autònoma de Barcelona: Port d´Informació Científica (PIC)

[64] The Grid: A System of Tiers. https://home.cern/about/computing/grid-system-tiers

[65] HPC (High Performance Computing): computación de alto rendimiento

Promoting data policies for free and open access means investing in a certain infrastructure for long-term storage and data processing [2:13]. Grid systems were designed to share resources across communication channels creating large scale computing clusters. Cloud computing results in somewhat the evolution of Grid to the abstraction of services provided over the internet (SaaS, PaaS[66], IaaS[67], etc.) Public clouds managed by private companies such as Google, Amazon, Microsoft or IBM among others, offer resources to provide solutions as services. They manage their own infrastructure to give such services in the so-called cloud. Private and public clouds are suitable as well as solutions for scientific installations. The inconvenient still faced nowadays is that the cost depends on the types of operations carried out and therefore very difficult to plan and foresee in advance.

2.7 Summary

The use of commercial SCADAs in industry is extensive and highly productive. However, these do not fully cover the requirements of large installations such as light sources who traditionally have often chosen other solutions. They have evolved from implementing multiple and heterogeneous technologies for different purposes to international collaborations trying to maximize the output by sharing efforts between different institutes. This is the case for control and data acquisition systems, and to same extent data processing and analysis. Unfortunately, user facilities do not often foresee the data processing and analysis services yet. Each group assumes the effort for most data processing and analysis, duplicating somehow resources.

Ethernet has evolved to become the standard fieldbus. The optimized design and maintenance of data networks, fieldbuses, deterministic networks and even high precision synchronization networks are critical success factors of control systems.

Supervision, control and data acquisition, as well as data processing and analysis clusters are dominated by Linux systems, often somehow virtualized, and with the Python programming language as a constantly growing and already a big player in the market. Both Linux and Python are proven, cost-efficient and open source, what is an important factor in scientific communities unlike industrial environments.

2.8 References

[2:1] P. Clout. "Distributed Computers in Accelerators Control Systems", Proceedings of the seventh IFAC Workshop, Bad Neuenahr, Germany, 1986.

[66] PaaS: Platform as a Service

[67] IaaS: Infrastructure as a Service.

[2:2] L. Casalegno, J. Coperus, A. Daneels, Ch. Serre, C. H. Sicard, P. Skarek, "Distributed software architecture applied to the LEP preinjector controls", Proceedings of the seventh IFAC Workshop, Bad Neuenahr, Germany, 1986.

[2:3] R. Fielding, "Architectural Styles and the Design of Network-based Software Architectures," Ph.D. Dissertation, University of California, Irvine, 2000.

[2:4] A. S. Tanenbaum and R. van Renesse. "Distributed operating systems". *ACM Computing Surveys*, 17(4), Dec. 1985, pp. 419-470.

[2:5] B.R. Mehta, Y. Jaganmohan Reddy, "Industrial Process Automation Systems". 2014, Butterworth-heinemann.

[2:6] L. Dalesio, M. Kraimer, S. Lewis. D. Murray, W. Watson, M. Clausen, J. Dalesio, "The experimental physics and industrial control system architecture. past, present and future". Nuclear instruments and methods in physics research, 352(1):179-184. 1994.

[2:7] A. Götz, J. Meyer, E. Taurel, J. M. Chaize, P. Verdier, F. Poncet, M. Ounsy, N. Leclercq, A. Buteau, C. Scafuri, M. Lonza, D. Fernández-Carreiras, J. Klora, T. Kracht, "Future of Tango", Proceedings of ICALEPCS 2007, Knoxville, Tennessee, USA.

[2:8] T. Coutinho, G. Cuní, D. Fernández-Carreiras, J. Klora, C. Pascual-Izarra, Z. Reszela, R. Suñé, A. Homs, E. Taurel, V. Rey. "Sardana, the software for building SCADAS in scientific environments". Proceedings of ICALEPCS 2011 (p. 607). Grenoble, France.

[2:9] J. Serrano, M. Cattin, E. Gousiou, E. van der Bij, T. Włostowski, G. Daniluk, M. Lipiński, "The White Rabbit Project", Proceedings of IBIC 2013. Oxford. U.K.

[2:10] D. Fernández-Carreiras, F. Becheri, S. Blanch, T. Coutinho, G. Cuní, J. Klora, C. Pascual-Izarra, S. Rubio-Manrique, R. Suñé. "Alba, a Tango based control system in Python". Proceedings of ICALEPCS 2009 (p. 709). Kobe, Japan.

[2:11] C. Pascual-Izarra, G. Cuní, C. Falcón-Torres, D. Fernández-Carreiras, Z. Reszela, M. Rosanes. "Effortless creation of control & data acquisition graphical user interfaces with Taurus". Proceedings of ICALEPCS 2015 (p. 1138). Melbourne, Australia.

[2:12] George Gilder. "The information factories", Wired. October 2006.

[2:13] P. Arzberger, P. Schroeder, A. Beaulieu, G. Bowker, K. Casey, L. Laaksonen, D. Moorman, P. Uhlir, P. Wouters. "Promoting Access to Public Research Data for Scientific, Economic and Social Development". Data Science Journal, Volume 3, November 2004.

3 A SYNCHROTRON AS A LARGE SCIENTIFIC INSTALLATION

A synchrotron is a so-called large scientific installation to produce light, or more precisely electromagnetic waves of a wide frequency spectrum; the synchrotron radiation with a particular interest in X-Rays for scientific use. X-rays are photons of a short wavelength and high energy –the shorter the wavelength the greater the energy[68]-, very suitable for carrying out experiments at atomic scale, looking at the interaction with the electrons of the atoms. The Beamlines are devoted to a type of experiments and optimized for a given range of wavelengths. X-rays allow the study of material sciences, molecular structures, magnetism, life sciences, cells, etc. This domain is continuously evolving with new detectors, synchronization capabilities, sample environments and in general the adoption of new technologies.

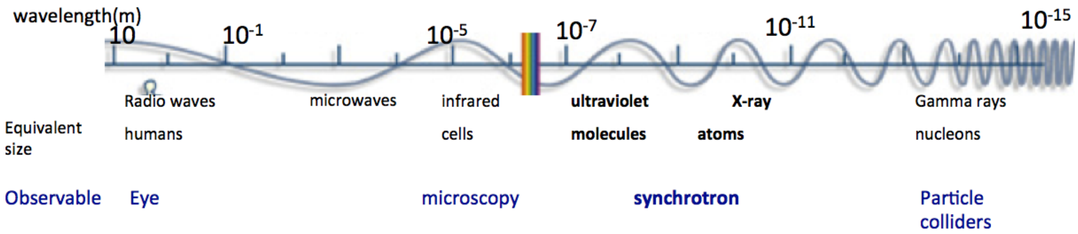


Figure 3-1: Electromagnetic wavelength spectrum

There are several synchrotrons in Europe, among others: ESRF and Soleil[69] in France, Diamond[70] in UK, PetraIII (DESY), BESSY[71] and ANKA[72] in Germany, SLS[73] in Switzerland, Elettra[74] in Italy, MAXIV in Sweden, and ALBA in Spain.

3.1 A particle accelerator for the production of X-Rays and the operation of Beamlines and experimental stations.

A particle accelerator is a machine to accelerate particles electrically charged to high energies at relativistic speeds close to the speed of light. They have many applications from fundamental research, high energy physics to applied physics, therapy, etc. One of the firsts purposes of particle accelerators was high energy physics, in particular colliders such as LHC[75] at CERN.

---

[68] E= hc / λ :where h is the Plank constant, c the speed of light and λ the wavelength. E(eV)= 1.2398/ λ(μm). https://en.wikipedia.org/wiki/Photon_energy
[69] Synchrotron Soleil. Paris, France. http://www.synchrotron-soleil.fr
[70] Diamond Light Source. Oxford, United Kingdom. http://www.diamond.ac.uk/Home.html
[71] BESSY II, Berlin, Germany. https://www.helmholtz-berlin.de/quellen/bessy/index_en.html
[72] ANKA, KIT, Karlsruhe Institute of Technology. Karlsruhe, Germany. http://www.anka.kit.edu
[73] SLS. Swiss Light Source. Paul Scherrer Isntitut, Villigen, Switzerland. http://www.psi.ch/sls
[74] Elettra Sincrotrone Trieste. Italy. https://www.elettra.trieste.it
[75] LHC: *Large Hadron Collider* at CERN, Geneva, Switzerland. http://home.web.cern.ch

These machines accelerate particles and/or anti-particles (protons in the case of the LHC) and make them collide at certain points where the detectors are, and the experiments take place[76]. The collisions generate new particles that are detected, discriminated and analyzed by instruments designed for that purpose. Synchrotrons are another category of particle accelerators, where a single beam of charged particles, usually electrons, are accelerated up to several Giga-electron-Volts (GeV) and stored in a Storage Ring, a circular (polygon-shaped) vacuum chamber with magnets and diagnostics (Figure 3-2, Figure 3-3). When going through the magnetic fields, the electrons lose energy which is emitted in form of photons: this is the synchrotron radiation (also known as synchrotron light). This synchrotron radiation is used to carry out experiments at the Beamlines.

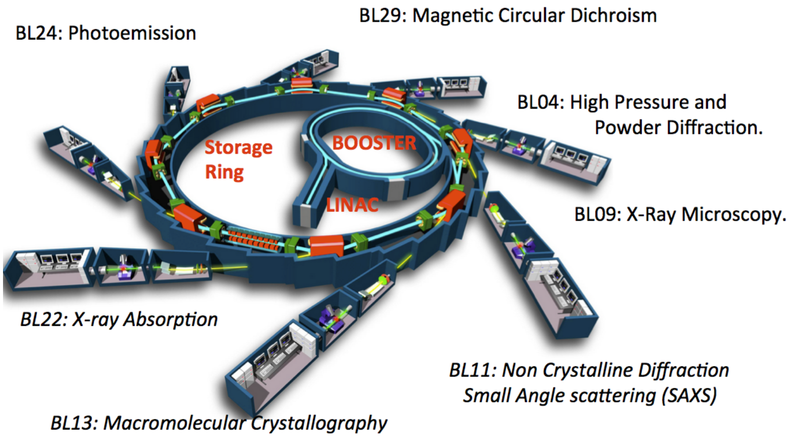


Figure 3-2: Schematics of a synchrotron, including seven light sources installed at ALBA (Source: Soleil and ALBA)

[76] In the case of LHC, 2 proton beams are accelerated to 7 TeV each by means of superconducting magnets, of 8.5 Tesla working at 1.5 Kelvin.

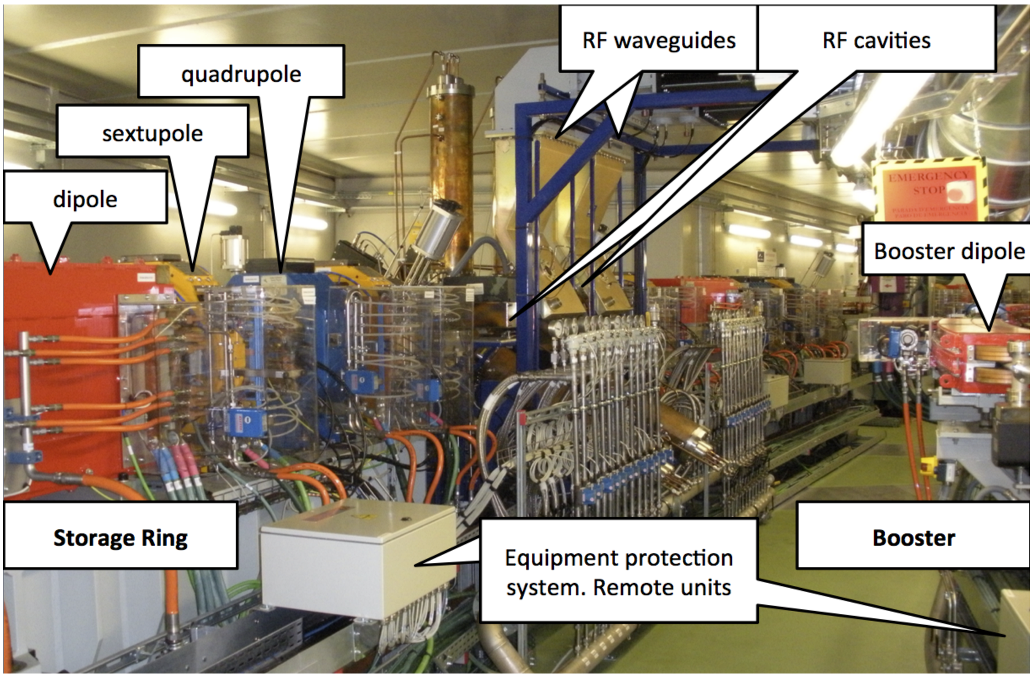


Figure 3-3: ALBA tunnel. Left: the Storage Ring with two RF cavities in the center. Right: Booster.

The synchrotron radiation is formally defined as the electromagnetic field irradiated by relativistic charged particles at near the speed of light (relativistic factor $\gamma >> 1$). The particles when deviated by the magnetic field lose energy and emit photons in a cone with a tangential to the field trajectory and with an angle approximately $1/\gamma$.

X-ray beams at a Beamline reach a brilliance of several orders of magnitude larger than a hospital X-ray source. Brilliance is defined as the number of photons per area and time, and assuming the divergence of the beam. Current Beamlines handle 10^{12} highly monochromatic photons/sec beams or higher, depending on the source and on the configuration of the Beamline.

ALBA is taken here as the example for the synchrotron explanation, although any other would be valid. The links to the web pages of the main installations in the footnotes provide more detailed information and explanations of the working principles.

Electrons are produced by a hot tungsten filament, accelerated at 100 MeV by the linear accelerator (Linac), later injected into the Booster Synchrotron where they are accelerated to 3 GeV and finally injected into the Storage Ring until the nominal current of 250 mA. This injection process operates at three Hertz repetition rate. When working in Top-Up mode, a reinjection is carried out every 20 minutes and therefore the beam and the thermal load is seen constant at the Beamlines preventing mechanical drifts in the optical elements.

A particle accelerator works in high vacuum. A complex system with ionic pumps, gauges and protection systems reach pressure ranges around 10^{-10} mbar. There are four types of magnets to focus and steer the electron beam. Dipole magnets that make the electron beam turn, making the accelerator a polygon with a dipole at each vertex; the quadrupole magnets to focus vertically and horizontally the beam and sextupoles to correct deviations on the energy of certain particles. An additional set of magnets -the vertical and horizontal correctors- keep the beam in orbit, with corrections for deviations of the order of tenths of micron. All these electro-magnets are powered by power converters with complex requirements in terms of precision and stability[77].

Insertion devices: Synchrotron radiation is a parasitic effect in high energy physics accelerators, and this is one of the reasons of their long perimeter. However, this effect is used at synchrotrons and free electron lasers to produce light[78] to be used later at the experimental stations. In 3rd generation synchrotrons, the majority nowadays, the X-ray source is no longer the dipole but a device (insertion device or ID, Figure 3-4) consisting of 2 yaws of arrays of magnets one in front of the other, creating successive opposed fields, to make the electrons oscillate and hence produce a higher photon flux. Depending on the disposition of the magnets, the emitted photons can be accumulated at every oscillation (in this case the ID is known as a Wiggler). On the other hand an ID can have shorter periods and depending on the distance between opposite magnets generate interference patterns at every oscillation cancelling out certain wavelengths and accumulating others and their harmonics (in this case the ID is known as Undulator). Insertion Devices are specifically designed for different purposes, for example for optimizing the brilliance at certain energies, the divergence, or for polarizing the light in a certain way.

---

[77] in the order of a few parts per million in ripple and stability always depending on the magnet type and function.
[78] Infrared, visible, ultraviolet and X-Rays.

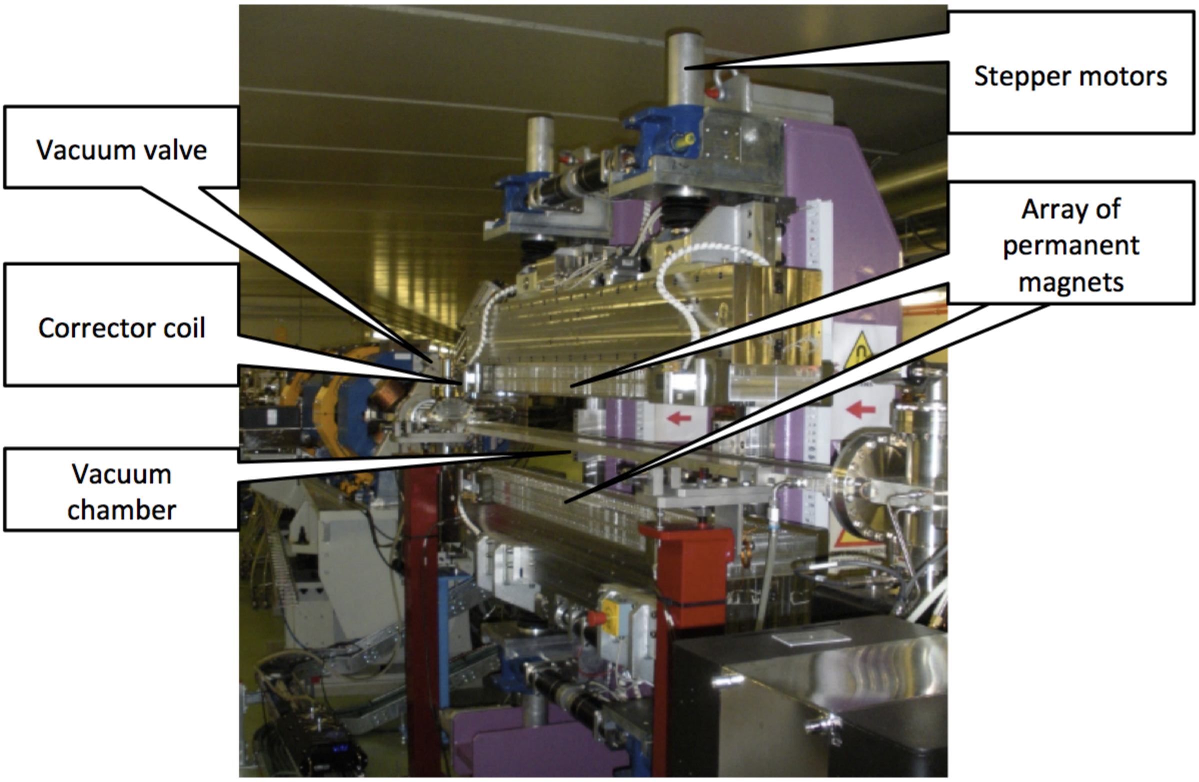


Figure 3-4: Insertion device or undulator[79] (Picture: AppleII ID at ALBA)

Radiofrequency (RF): Electrons lose energy at every magnetic field they interact with. This energy shall be given back to the electron beam in order to keep the orbit and the characteristics of the beam. The radiofrequency system (RF)[80], re-accelerate the electrons to their nominal energy. The Storage Ring of ALBA has six cavities and the Booster has one. The Linac has of course its cavities and accelerating sections as well. The radiofrequency cavities are inserted in the vacuum chamber in the electron beam trajectory. The radiofrequency signal is amplified to hundreds of kW, and transported to the cavities by a complex system of waveguides. The frequency chosen depends on the characteristics of the accelerator and on the technology of the RF amplifiers. The RF plants are one of the subsystems more critical and sensitive. A failure will in most cases derive in a beam loss. In absence of RF power, the beam will be lost in a few milliseconds. Therefore, the RF subsystem is the preferred way to stop the beam in case of an interlock, for example from the Personnel Safety System or the Machine Protection System, and is essential to be reliable to meet the requirements of the availability of the beam. The RF signal is produced in a single generator and transmitted to all RF plants. Although not common, there can be more than one generator synchronized by an external signal given by the Timing system introduced in the next paragraph.

---

[79] ALBA Synchrotron. IDs: http://www.cells.es/en/accelerators/insertion-devices

[80] ALBA Synchrotron. RF: http://www.cells.es/es/aceleradores/sistemas-de-rf

Timing: Particle accelerators and Beamlines need a precise synchronization. Injection and diagnostic elements need to be triggered with a resolution of a few nanoseconds in most cases, and occasionally in the range of picoseconds. The measured *jitter*[81] must be of a few tens of picoseconds depending on the application. The first element to synchronize is the Linac with the electron gun. The beam then is injected into the Booster by dedicated pulsed magnets and power supplies: Kicker and Septum. The Septum provides a magnetic field a few milliseconds long, the Kicker only of a few microseconds. Their power supplies must be synchronized with the Linac and other elements for the injection. The Booster accelerates the beam from 100 MeV to 3 GeV, and later is injected into the Storage Ring. The magnetic fields in the Storage Ring are constant because the energy is constant. The Booster increases the magnetic field in the magnets as the energy of the beam is increasing in order to keep the orbit. The bending radius decreases increasing the magnetic field and increases increasing the beam energy.
Once reaching 3 GeV, again with a Septum and a kicker, the beam is extracted from the Booster to a second transfer line[82] and injected in the Storage Ring with another septum and four kickers (Figure 3-5). The number of pulsed elements may vary in different accelerators depending on the configuration and type.

[81] *jitter*: The fluctuation of the arrival of the signal with respect to the nominal (expressed normally in values root mean square or RMS).
[82] BTS: Booster to Storage Ring transfer line.

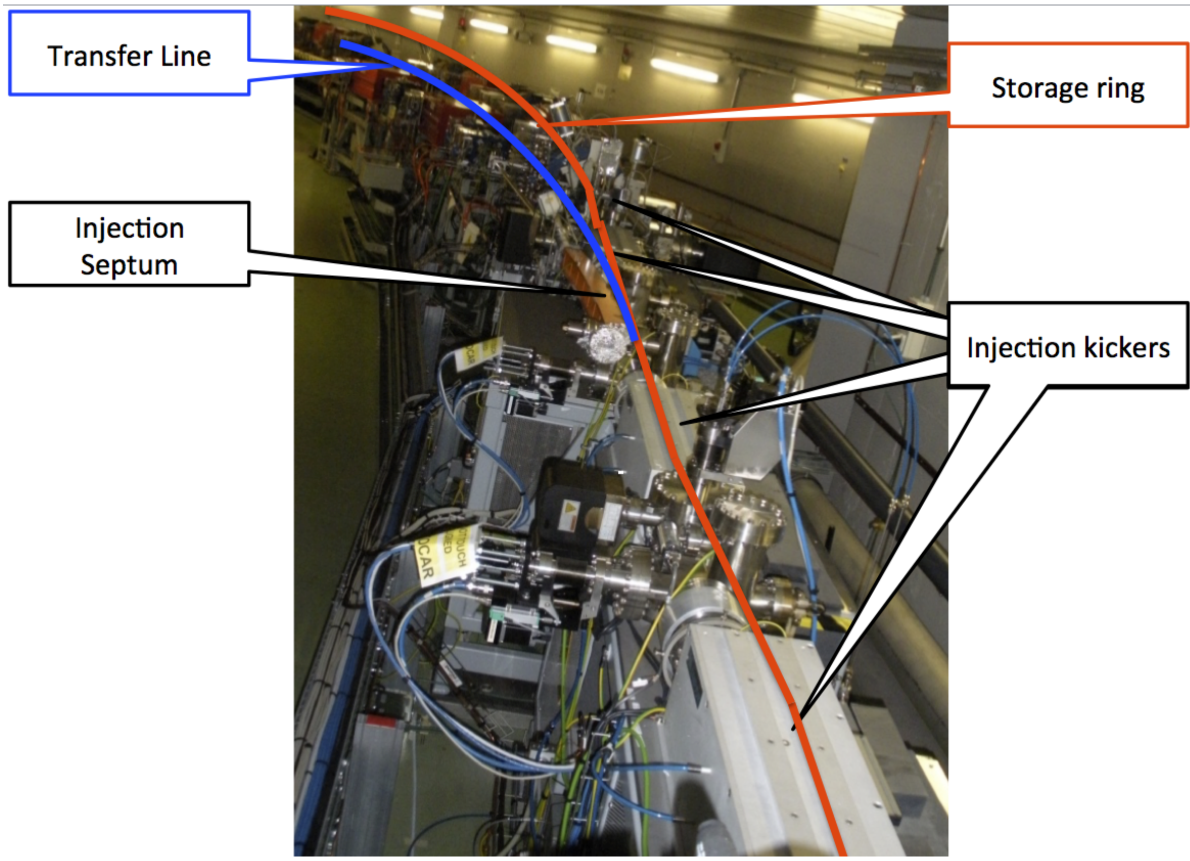


Figure 3-5: Example of injection instrumentation (ALBA). The electron beam comes from the Booster through the transfer line (blue) and are injected into the Storage Ring (red)

High and Ultra-high vacuum: Both particle accelerators and Beamlines work with high or ultra-high vacuum in the vacuum chambers. The pressure level goes down to 10^{-9}, 10^{-10} mbar. To reach such a low pressure, the chambers shall be designed accordingly and baked-out. The elements inside the chamber shall be designed following certain protocols and using purpose specific materials. Then the vacuum is achieved by continuous pumping and the control system reads pressures, and controls the vacuum elements such as pumps, gauges, protection systems, valves, temperatures etc. These elements are distributed in the vacuum chamber, occasionally several of them per meter so the vacuum control subsystem and the equipment protection system have a large number of field elements. Ion pumps and gauges ionize the residual gas with a high voltage (in the order of thousands of volts, typically 7000V), and read the small current (ions) flowing between the anode and the cathode. The accelerators, front-ends, Beamlines and experimental stations include vacuum tight pneumatic valves, separating vacuum sectors in order to protect upstream sectors from an accidental venting[83] and for maintenance purposes. The accelerators of a facility like ALBA comprises several hundreds of pumps, valves, temperatures, flow meters, interlocks, etc. In total more than 7000 signals are

[83] Venting: Vacuum is lost and pressure increases up to atmospheric values.

monitored and archived in the vacuum system environment. Every Beamline has also special requirements in several disciplines, including vacuum.

Diagnostics: Instrumentation and diagnostics devices acquire and analyze signals produced by the effects of the electron beams. One of the most relevant in particle accelerators are the *electron Beam Position Monitor* (eBPM), that measure the horizontal and vertical position of the electron beam. eBPMs are usually formed by four capacitive buttons, read by a purpose specific high precision electronics: *Libera, Instrumentation Technologies*[84]. This instrument reads the analog signals by ADCs at 118 MHz and provides operational modes for continuous fast readout at 10 kHz. The orbit correction implements a global feedback system between these modules to read the position and the vertical and horizontal steering magnets power supplies. In the case of ALBA these feedback loops are performed at slow pace (1/3 Hz) or fast at 5 kHz (in 16 dedicated multicore CPUs running Linux). The eBPMs are also important in the protection systems, capable of detecting orbit deviations above the given thresholds and provoking an interlock to eventually kill the beam. When triggered by the timing system at the moment of a beam loss, eBPM electronics can also store valuable post-mortem data.
The measurement of the beam current is generally carried out by several devices depending on the required precision and bandwidth: the most significant are the FCT[85] for fast measurements and the DCCT[86] for slow and precise readouts. The FCT reaches up to GHz and the DCCT[87] gives a much higher precision in the Hz range. Other very common diagnostics devices are CCD[88] cameras that offer a two dimensional image of the beam for example in fluorescence screens (often invasive: they block the beam) or in synchrotron radiation monitors after a dipole magnet (noninvasive). There are many other diagnostics for the electron beams such as scrapers (sort of slits), beam loss monitors, etc. The particle accelerators shall ensure stability in the order of 10% of the size of the beam. This can be far below the micron range. The orbit feedback corrects different types of noise like big displacements such as thermal drifts or misalignments that may require a certain strength in the corrector magnets (in the order of mrad), and small vibrations coming from different sources. The Fast Orbit Feedback (FOFB) corrects these perturbations at a frequency of 5-10 kHz resulting in an attenuation below 100 Hz. On the contrary, the direct side effect is that higher frequencies get amplified. The FOFB reads the position from the BPMs at 10 kHz that is compared with the reference orbit in a set of 16 CPUs and the new set-points are calculated and sent to the correctors' power supplies (vertical and horizontal) at 5 kHz.

---

[84] Instrumentation Technologies: http://www.i-tech.si/
[85] FCT: Fast Current Transformer.
[86] DCCT: Direct Current, Current Transformer.
[87] https://www.cells.es/en/accelerators/diagnostics
[88] CCD: Charge-Coupled Device. https://en.wikipedia.org/wiki/Charge-coupled_device

Building Control system: HVAC[89] and cooling systems: In the scientific installations, the building control system has been traditionally outsourced, and kept apart from the rest of control systems. Particle accelerators and Beamlines are very sensitive to thermal instabilities. The temperature regulation specification for the tunnel is typically ± 0.5 degrees Celsius. Thermal drifts affect the vacuum chamber and therefore the radiofrequency fine-tuning. The temperature and humidity control systems inside the tunnel or Beamline hutches are crucial for the quality of the data of the experiments. A better regulation of these parameters and the crosscheck of temperatures and humidity during the analysis of the experimental data will improve the quality of the experiment and eventually understand and fix eventual problems. The water-cooling circuits follow complex dynamics that in case of malfunction may result in a brain-teaser with a complex diagnosis. These control systems are typically managed following pure industrial standards, with commercial SCADAs and PLCs. They include a collection of temperature measurements, flowmeters, pressure gauges and many other kinds of probes. However, the fact of being separated in a different physical network makes the correlation of data complicated, not to mention the regular system administration, backups, archives, etc. At ALBA, this has been work-rounded by a physical gateway and a service querying the Buildings' SCADA SQL Server database from the accelerators and Beamlines control systems. Future installations should share the same network and design these services from the beginning.

3.2 Beamlines and experimental stations

A Beamline is the set of optics and instrumentation to focus, monochrome and condition the photon beam and take it to the sample and the detectors in the environment and conditions that the experiment requires[90]. The photon beam travels through the front-end inside the accelerators tunnel to the optical hutch[91] of the Beamline. This lead-shielded hutch has the optical elements such as mirrors and slits, to shape and condition the beam. It also has diagnostics elements, attenuators and vacuum instruments. The experimental stations can be devoted to soft X-rays (energies below 4 keV) or hard X-rays. The design of a Beamline is always different from the others but depending on whether it is soft or hard X-rays it follows a different paradigm. Soft X-rays interact more with the particles and are more sensitive to the vacuum quality. Soft X-ray Beamlines work in Ultra High Vacuum (10^{-10} mbar). The usually

[89] HVAC: Heat Ventilation and Air Conditioning. Control systems for the building.

[90] In some contexts, the Beamline is only the optical part considered apart from the experimental station that handles the sample and the detectors. In other contexts, the concept Beamline includes the experimental stations as well. A Beamline can have several experimental stations.

[91] Hutch is a common name given to the protected room where the instrumentation is installed. Other common names are cabins or bunkers.

are equipped with a *grating monochromator*[92] to select the wavelength of the photons. The different energies are diffracted in different angles and selected by an *exit slit*. Hard X-rays Beamlines have often two hutches, the optics hutch that contains the mirrors and the monochromator and a safety photon shutter separating both hutches. The monochromator is often a silicon crystal (or a combination of two or more) that based on Bragg's law[93] allows selecting wavelengths with high resolution (about 10^{-4} $\Delta E/E$). The second crystal when exists allows fine-adjusting the height and angle of the beam, although it can induce vibrations and noise (Figure 3-6). In some cases, both surfaces are in the same silicon block crystal, so they are more robust in terms of stability, although less flexible in some particular cases when need to work at different energy ranges.

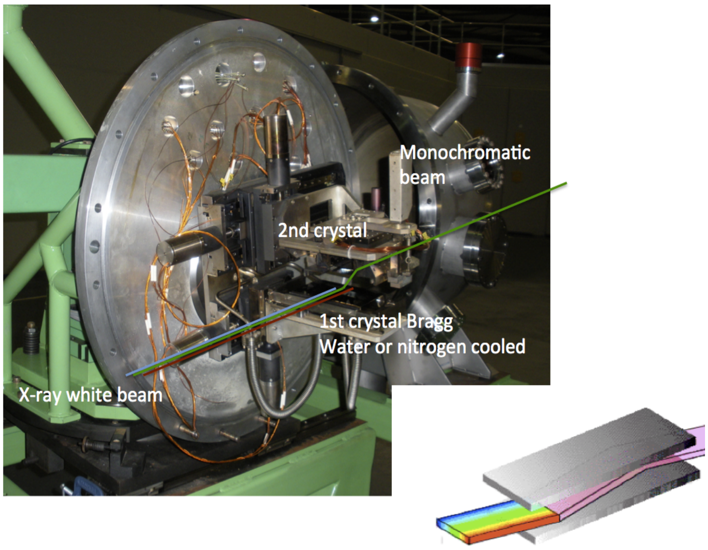


Figure 3-6: View of the inside of a hard X-Ray double crystal monochromator

Control System: The control system of a Beamline is independent from the others (Figure 3-7). It does not communicate with other Beamlines although it interacts with the particle accelerator at several levels. On one hand, the protection systems continuously verify that the operation is safe. The Personnel Protection System (PSS) will close the Safety Photon shutters, Front-End shutters or even stop the accelerator if detects a misbehavior in the operation of a Beamline, such as an intrusion, or a radiation level outside the shielded areas above the limits. These connections are made by redundant and diverse hardwires and by certified safety buses. The equipment protection systems (EPS) will close the Front End if it detects a misbehavior that can damage the instrumentation, the optics or any other element of the Beamline. For

[92] Grating monochromator. Silicon crystal with a coating of different materials that has a periodic pattern which splits and diffracts the beam into several directions. There are several types depending on the structure for different applications. They are extensively used in soft X-rays Beamlines.

[93] Bragg's law: $n\lambda=2d\sin$: https://en.wikipedia.org/wiki/Bragg%27s_law

example, the EPS will close the upstream sector valves if it detects a vacuum pressure above the limits. These types of communications are carried out by hardwire signals, but also by fieldbuses. Besides the protection systems, there are other crucial communications between Beamline and the accelerators: The operation of the insertion device. The insertion device is in the machine[94] and the machine is accountable for it. It actually has an impact on the quality of the electron beam and therefore the machine shall have the ultimate control. However, it is operated by the Beamline (after all it is the light source of the Beamline), which can make a continuous use, for example in spectroscopy experiments that require continuous changes of the energy. These control systems for accelerators and Beamlines are covered in chapter 4.

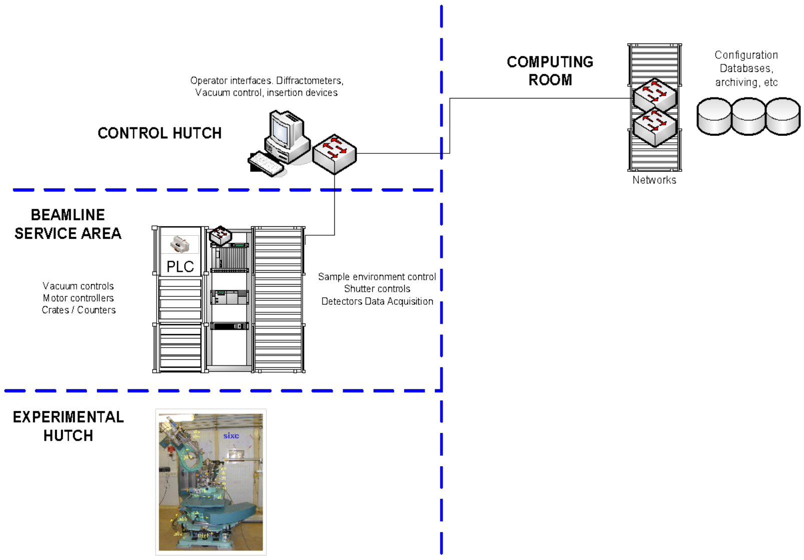


Figure 3-7: Distribution and architecture of the control system of a Beamline

Detectors are the key instruments in the experimental stations. Everyone has specific requirements but all require more and more temporal resolution. Time resolved experiments are carried out with several area detectors with a higher bandwidth. Nowadays 300 MB/s are common and the detectors in specific Beamlines in some synchrotrons reach already GB/s ranges[95]. The research in instrumentation and detectors initially oriented to other domains, for example High Energy Physics at CERN, are also used in light sources, synchrotrons and Free Electron Lasers. Besides, very specific developments are being carried out in particular to meet the requirements presented by the latter. Free Electron Lasers produce such as high number of photons in a very small fraction of a second, that the current paradigm for synchrotron light sources is no longer valid.

[94]In the argot of the synchrotrons, the accelerators are often referred to as the Machine.

[95] There are in fact projects proposing TB/s for the following years

Scientific grade CCD and CMOS cameras with a large detection area, small pixel size, combining several chips in the same detector and with several ADC channels per chip are extensively used at synchrotrons. They reach high bandwidths of several hundreds of MB/s and GB/s in certain cases.

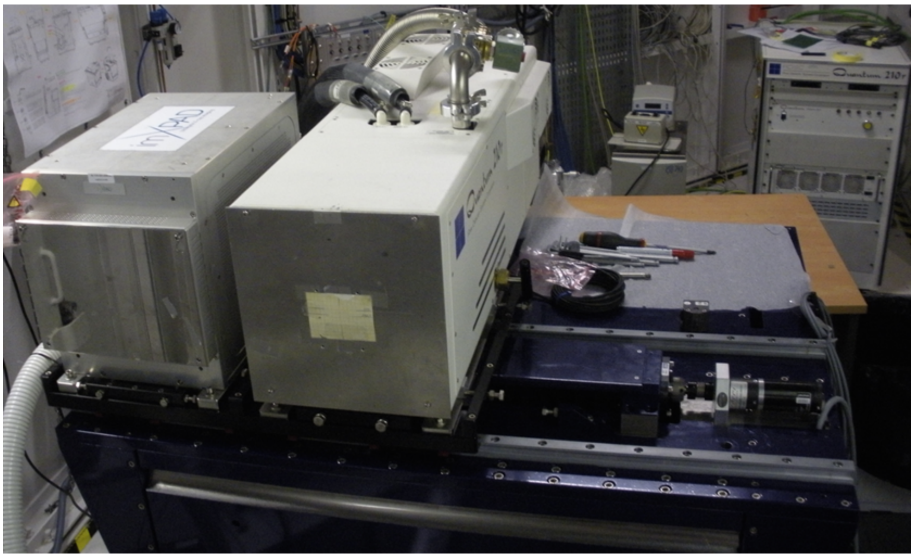


Figure 3-8: Configuration with 2 detectors for SAXS techniques installed at BL11/ALBA (2017). Left Pixel Array Detector ImxPAD, right 4xCCD ADSC

Pixel Array Detectors (PAD*)* detectors are getting very popular in experimental stations at synchrotrons. CCD cameras, CMOS and PAD detectors have pros and cons depending on the Beamline and on the experiment. PAD have normally a large pixel size (from 50 to 200 micros) and have blind stripes between the modules. On the other hand they count photons directly detected without needing a scintillator screen, so they can discriminate the noise and have a higher efficiency at certain energies giving better results than a CCD. The Figure 3-8 shows both detectors at ALBA-BL11[96], devoted to SAXS[97] and NCD[98]. The Quantum ADSC is made of four chips of four million pixels each. The ImXPAD is a 1.4 million pixel PAD that reaches 500 images/second. The chapter 5, covers the different detectors and associated data acquisition and control systems. Beamlines are constantly upgrading their requirements to be able to carry out new experiments. The latest upgrade of the Beamline (ALBA-BL11) included the upgrade of these detectors.

[96] http://www.cells.es/en/beamlines/bl11-ncd
[97] SAXS: Small Angle Scattering.
[98] NCD: Non Crystalline Diffraction

4 THE CONTROL SYSTEM

As introduced in chapter 2, the control systems for particle accelerators and other large scientific installations, have been traditionally developed “ad hoc” purpose specific to adapt to the hardware and particular requirements of every installation. Later in time, some components were reused in other installations leading to the assumption of “de facto” standards. Software pieces and applications were exported to new projects and workshops to discuss about challenges and solutions were organized, creating spaces for exchanging information, problems, solutions and creating communities. The most representative and one of the first was EPICS, created at the end of the eighties by Los Alamos National Laboratory in New Mexico in collaboration with Argonne National Laboratory in Chicago. EPICS is today a full toolkit and framework for the development of control systems for large scientific applications. Later, in the early 2000s TANGO was made available to the community. TANGO, based on CORBA was the evolution of the ESRF TACO[99] control system and was constituted as a collaboration when the Synchrotron Soleil decided to use it as the standard control system and joined the efforts of the ESRF. TANGO is today a successful growing collaboration, although still smaller than EPICS.

Also in the eighties, G. Swislow (Cambridge, MA) presented SPEC[100], an application for the diffractometer control that scaled out in the nineties to the control of full Beamlines at light and neutron sources. Unlike EPICS or TANGO, SPEC is commercial and the source code is not open. The success of SPEC comes from the wide support, the large and updated hardware catalogue, and the complete macro language and macro environment. SPEC offers also support and tools to integrate different type of diffractometers, such as two, three, four or six circles, kappa diffractometers, etc. SPEC can run stand alone or in combination with other control system infrastructures such as TANGO or EPICS,

4.1 The particle accelerators control systems.

The hardware of a particle accelerator is by nature distributed. The accelerator is installed inside a tunnel or a bunker, the shield for radiation. Most electronics, in particular the radiation sensitive, are normally installed outside the tunnel in cabinets at the service areas. The software is and shall be distributed as well. TANGO is organized in a client-server architecture, where clients are mostly running in workstations at the control rooms and servers run in IOCs[101],

---

[99] TACO: ESRF initial control system framework developed in the construction phase. TACO was based on RPC (Remote Procedure Call).
[100] SPEC: (http://www.certif.com)
[101] IOC: Input Output Controller. Largely used in EPICS terminology. An IOC is usually a computer, although it can be virtualized, with input output cards to readout field sensors and acquire data in general. A generic

which manage the access to the hardware, data acquisition and inputs/outputs (setpoints, regulation loops, etc.). The trend now is to virtualize the IOCs making extensive use of the newer technologies, such as internet of things (IoT). These IOCs with no direct access to the hardware (the access is through Ethernet) can run in virtual machines in the central data center. There are other important subsystems that are not necessarily directly related to EPICS or TANGO such as the Equipment Protection, Machine Protection, Personnel Protection, Timing, Fast Interlocks etc. as represented in Figure 4-1.

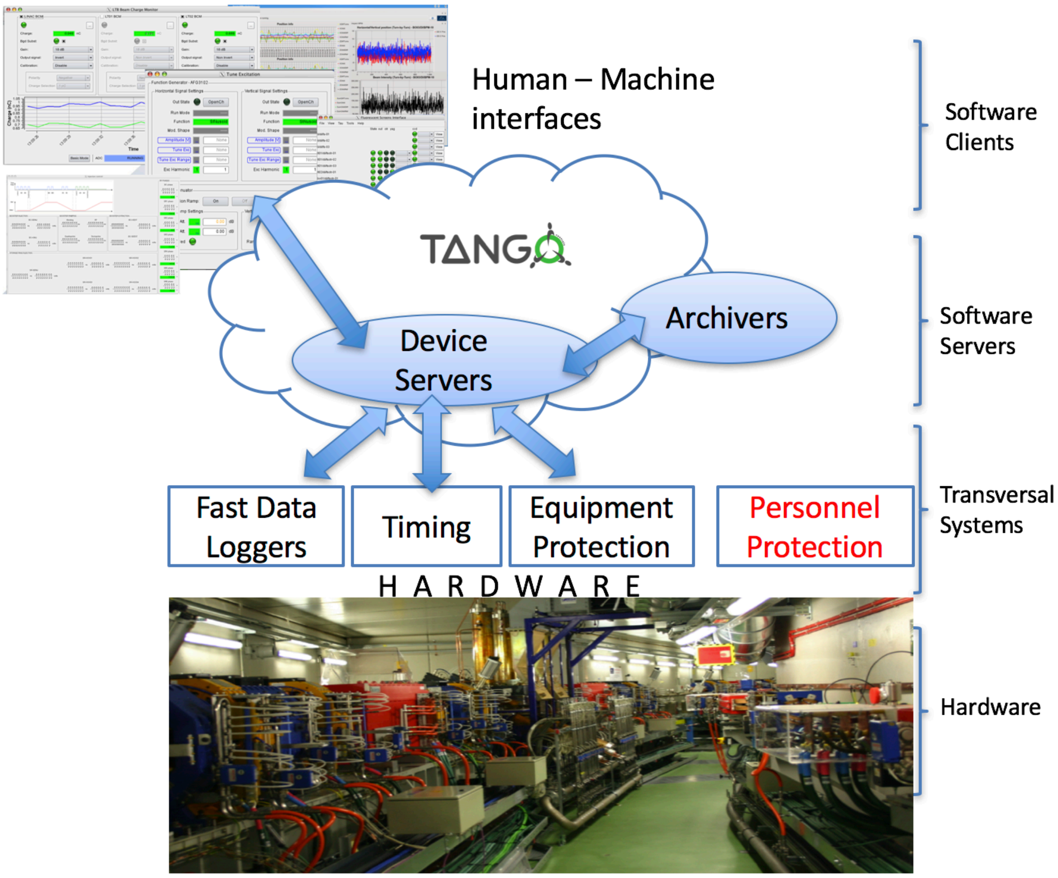


Figure 4-1: Conceptual Diagram of the building blocks of a control system.

The most important subsystems of a control system of a particle accelerator were introduced in the previous chapter (Figure 4-2): Vacuum, Power Supplies, Radiofrequency, Diagnostics, Timing, Equipment Protection System, Personnel Safety System, Alarm Handlers, historical Archivers, Fast data Loggers, etc. These protection systems, archiving and alarm handling are transversal to all the other subsystems. The domain of particle accelerators can have different

---

example is an industrial PC diskless (boot remotely through the network) with several input output cards such as ADCs, digital inputs, counters, etc.

uses with specific hardware, for example Insertion Devices in Synchrotrons and Free Electron Lasers.

These control subsystems are described in this chapter, taking often the example of the ALBA Synchrotron -with a Linac, a Booster and a 268 meters long Storage Ring- although these concepts can be applied to most medium and large size particle accelerators [4:1][4:2][4:3]. The system is divided in 16 sectors, with the controls electronics installed in cabinets in the service area, outside the shielding in the inner part of the tunnel circle. The control system comprises about 350 42U nineteen inches' cabinets, 150 PC type computers (cPCI and industrial PCs). As a general rule, cPCI chassis have data acquisition I/O cards and Timing receivers. Industrial PCs are installed where triggers are not needed, such as vacuum or insertion devices.

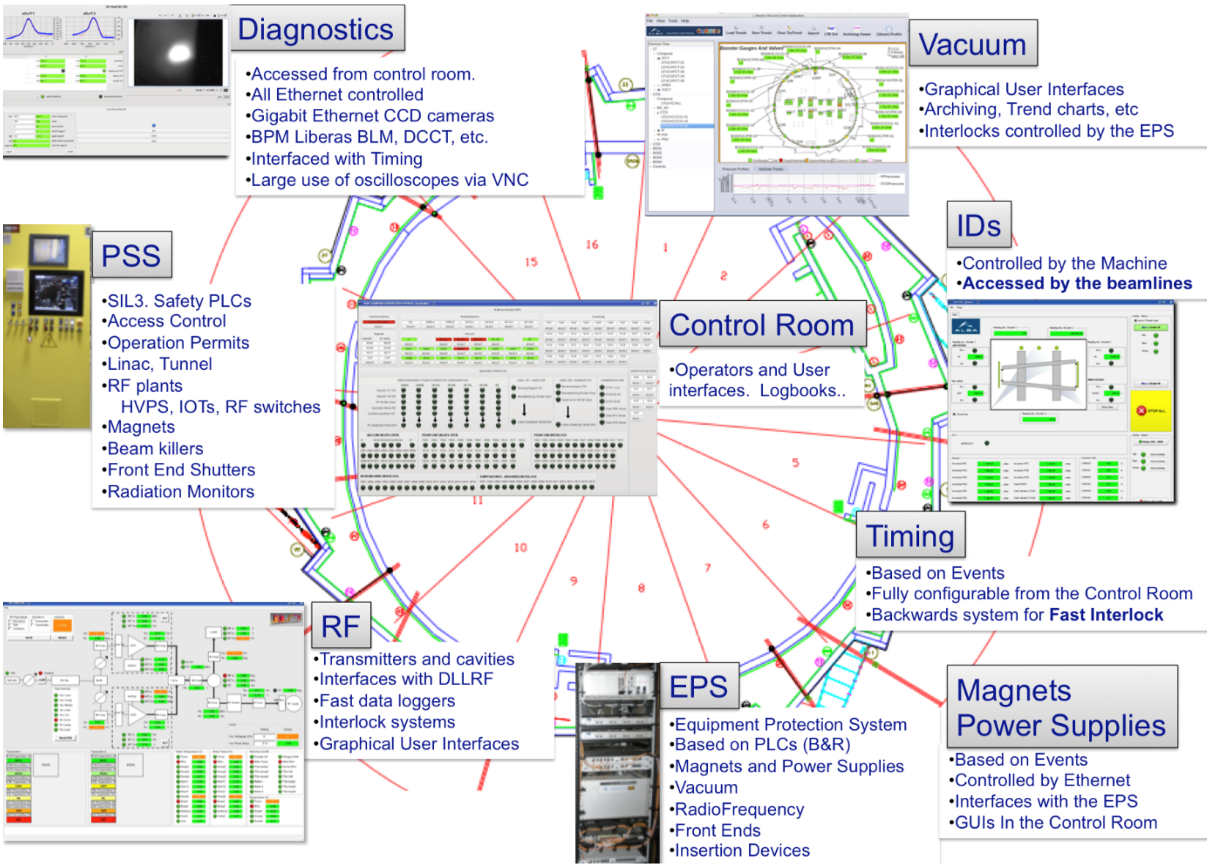


Figure 4-2: Components and subsystems of the particle accelerators controls.

4.1.1 The vacuum control system

The vacuum control system is present in all particle accelerators and Beamlines. It is largely distributed and comprises typically a large number (several thousands) of process variables. Although there are many instruments and devices involved, the number of different types is kept reduced in order to moderate maintenance costs. As a reference, ALBA's Storage Ring has about 170 ion pumps[102], 70 *cold cathode gauges*[103], and about 35 *Pirani gauges*. There are also about 45 sector valves and more than 500 thermocouples to monitor the temperature of the vacuum chamber. Other devices such as RGA[104], used to analyze and histogram different ions, or other type of pumps like the *Titanium Sublimation Pumps* (TSP), used in certain cases for Ultra High Vacuum requirements, can also be part of the system although in smaller quantities. In addition to all these components, flowmeters, the aforementioned thermocouples (usually K or T type), or other temperature sensors, such as the resistive pt100 or pt1000, are often as well part of the system.

All these instruments and sensors, as well as opening and closing valves, are controlled by PLCs, which following given pressure and temperature thresholds and logic, interlock upstream devices that can go until stopping the electron or photon beam in the most critical cases. Pirani gauges interlock cold cathode gauges, which interlock ion pumps for their protection. The sector valves close after a combination of read values from ion pumps and cold cathode gauges. Although Ethernet is the standard fieldbus, still today vacuum equipment is offered with serial line connections (RS232, RS422 and RS485), for which the system has to foresee a large quantity of serial ports. In the case of ALBA, the system includes a PC with 16 or 24 ports per sector for this purpose. This trend will likely change in a short time, and the connection will be done by Ethernet.

4.1.2 Power supplies control system

Power supplies are a main component of every particle accelerator. Most do not require a fast communication link, except if they need to be ramped or are part of a fast feedback loop where they require a fast communication channel and they can be triggered as well. In the particular example of the ALBA synchrotron, they follow the standard and are all linked by Ethernet with the exception of the controllers of the corrector coils which required lower latency and a deterministic link. There are more than 400 power supplies comprising Booster, transfer lines, and Storage Ring. They can power one magnet, a family or even all of a class like the bending magnets that are all connected in series and powered by a single supply. The connection with the control system relies on a network *socket*[105] implementing a predefined protocol. Using Ethernet as the standard makes the installation and maintenance simpler. However standard Ethernet switches are not yet designed to ensure 10 kHz deterministic read/write operations.

---

[102] https://en.wikipedia.org/wiki/Ion_pump_%28physics%29
[103] https://en.wikipedia.org/wiki/Cold_cathode
[104] RGA: Residual Gas Analyzer: mass spectrometer. https://en.wikipedia.org/wiki/Residual_gas_analyzer
[105] Network socket: Software endpoint used to transmit data over the network. Typically on protocols TCP, UDP or IP. https://en.wikipedia.org/wiki/Network_socket

There are indeed adaptations of the protocol to make it faster and deterministic but such a system needs to be adapted and commissioned accordingly. Therefore, a specific solution based on the proprietary PSI[106] interface was implemented for 176 corrector magnets involved in the fast orbit feedback of the Storage Ring. The solution adopted relied on specific electronics on cPCI chassis, and IndustryPack (IP) modules [4:4] with a Spartan I FPGA that uses a dedicated fiber optics link transmitting a Manchester[107] encoded protocol to the power supply controller. This interface, although installing and running in a few facilities, is nowadays discontinued and no longer available and has been superseded with new version incorporating new hardware, communication links and software.

The overall control system is also distributed with TANGO device servers running on cPCIs located at the service area and the human-machine interfaces developed as configurable forms with different views that run typically in the control room workstations.

4.1.3 The Radiofrequency System

The radiofrequency system (RF) function is to accelerate the electrons in order to give them more energy or make them recover the energy they lost in the magnetic fields they found on their way. A particle accelerator has at least one RF cavity powered by a RF Transmitter with at least one power supply. A transmitter in the jargon is the instrument to produce high power RF signals and feed the cavities. The particle accelerators at ALBA include a RF cavity in the Booster and six in the Storage Ring all mounting Inductive Output Tubes (IOT[108]), with 80 kW nominal power each.

The supervision and control systems run on 3U and 6U cPCIs (Lyrtech VHS-ADC with FPGA Xilinx Virtex-4 for the Low Level RF regulation of amplitude and phase LLRF[109]). The regulation is done after a modulation/demodulation IQ (*in phase quadrature*[110]) carried out in the aforementioned FPGA[111]. The RF signal is converted to IF digitalized by a fast ADC and demodulated to IQ ($I = A.cos\ \varphi_0\ ;\ Q= A.sin\ \varphi_0$), used as the input to the PI[112] controller [4:5]. The system also regulates the cavity resonance by controlling a stepper motor acting on a plunger. This low-level control systems require often specific provisions, hardware and exceptions. The Lyrtech card was only available in cPCI 6U and drivers were only available for Windows. The control system infrastructure must be ready to accept these exceptions by

[106] PSI: Paul Scherrer Institut (http://www.psi.ch). Villigen. Switzerland.
[107] https://en.wikipedia.org/wiki/Manchester_code
[108] IOT: Inductive Output Tube: https://en.wikipedia.org/wiki/Inductive_output_tube
[109] LLRF: Low Level Radio Frequency. Amplitude and Voltage regulation system of the RF signal in the cavities.
[110] https://en.wikipedia.org/wiki/In-phase_and_quadrature_components
[111] The analogue input/output, ADC/DAC, downsampling and deterministic regulation can only be done by a small number of commercial FPGA boards [4:5].
[112] *Proportional Integrator*, without Derivative component

accommodating the required hardware and supporting several operating systems. Even if the standard specifies Linux and is followed by more than 90% of the boxes, Exceptions requiring Windows are practically unavoidable. TANGO natively supports Windows and therefore seamlessly solves this issue.

4.1.4 The control system of Insertion Devices

Insertion Devices (ID) are arrays of permanent magnets that make the electron beam oscillate multiplying the generation of light. As introduced in the previous chapter, they are characteristic from the 3rd generation light sources.

Regarding the control system, an ID is basically a set of motors that open and close the gap between the jaws of arrays of magnets. They also have corrector coils and their power supplies, vacuum pumps, limit switches, etc. There are several types, the magnets can be in vacuum, or they can have extra axes to control de detuning of the alignment of opposite magnets and produce different types of polarized light. There are also other types without permanent magnets but with coils (occasionally superconducting). Therefore, the control system manages motors, power supplies and eventually vacuum, temperatures, limit switches and other safety devices connected to the equipment protection system. The figure of merit is in the precision, speed and overall performance of these motions, and their integration with the control and data acquisition systems of the beamlines.

4.1.5 Diagnostic systems

As mentioned in the previous chapter, particle accelerators and Beamlines require a large variety of diagnostics systems and Ethernet accessed oscilloscopes that can monitor a large variety of instruments, such as Fast Current Transformers (FCTs) for monitoring the current of the beam and the filling patterns.

Diagnostic devices often have their own readout electronics. For example, the DCCT controller provides an output voltage in order to feed it to an ADC integrated into the control system. This can be digitalized with a standard 16bit ADC in a standard Linux IOC cPCI, or depending on the application and on the quality of this signal could be digitalized with a higher precision 20 bits ADC module.

The Libera electronics is an autonomous device with an analogue 4x 16bit 117 MHz channels[113]. Each of these boxes reads a BPM[114] (up to four BPMs in the newer versions), that as an example can reach up to 120 at the ALBA Storage Ring. The typical sampling rate for

[113] Libera docs: http://www.i-tech.si/accelerators-instrumentation/libera-brilliance-plus/documentation_1#
[114] BPM: Beam position Monitor (four channels in order to give values in both horizontal and vertical axes)

fast acquisition is configured at 10 kHz, dictating somehow the sampling rate for the Fast Orbit Feedback (FOFB) of the main accelerators around the world (most have been using this technology in the past years). All Libera boxes are interconnected in a sort of a redundant private network that results in a reflective memory behavior used by the *FOFB*.

Other key elements are the two-dimensional detectors CCD/CMOS[115] type cameras. The cameras are usually monochromatic progressive (unlike the interlaced very popular amongst the general public). The design of the ALBA control system discarded the analogue video cameras and encouraged and standardized the Gigabit Ethernet (GigE) protocol, in particular *Basler Scout 1000-30gm*. These multipurpose cameras serve in the invasive fluorescence screens (FS), non-invasive Optical Transmission Screens (OTR), synchrotron radiation monitors and many other devices. The number of devices required depends on the use, but an approximate rule of thumb is one every 20 meters of the accelerator (30 in the case of ALBA) and about 5 per Beamline. This particular Basler model has a 1034x779 pixels ASIC CCD transmitting at 30 full frames per second and externally triggered, which is challenge to be taken into account during the design of the network and the control servers because the images are transmitted synchronized at the same time usually by a UDP protocol, producing a peak load that the network has to handle at every trigger. The diagnostics cameras are usually triggered at each injection (usually at frequencies of a few Hz), but they can also acquire series of images after a single trigger. They can also profit from Power over Ethernet (PoE) which simplifies the cabling. This seems a clear advantage upfront but based on experience, the PoE capability of the switches is not so reliable as the transmission link, so in several occasions the power cable was still required after a failure of the PoE.

4.2 Transversal systems. Interlocks and synchronization

The Equipment Protection System (EPS[116]) manages permits and interlocks designed to protect the hardware and the instrumentation from any possible damage derived from the operation. ALBA EPS was designed relying on B&R[117] PLCs with CPUs in the service area, connected by X2X fieldbus to remote IO inside the tunnel in lead-shielded boxes (neutrons and X-ray radioactive environment). The CPUs are interconnected by the Ethernet PowerLink deterministic network, opensource and adopted by B&R. Other Synchrotrons use other manufacturers being Siemens S7 with Profibus and Profinet the market leaders.

[115] CMOS (Complementary Metal Oxide Semiconductor (CMOS): Technology to construct integrating circuits very popular nowadays for imaging sensors. https://en.wikipedia.org/wiki/CMOS
[116] EPS: Equipment Protection System.
[117] B&R Automation. Austrian company providing sensors PLC and other electronic devices. http://www.br-automation.com/en/

The Personnel Protection System (PSS[118]) monitors the radiation levels outside the shielded areas and ensures that these areas are clear of personnel during operation. This protection system follows the specific norm IEC-61508 for the industrial processes control and automation functional safety.

Both EPS and PSS are transversal systems based on PLCs. However, they are separated and physically and functionally independent from each other. The EPS is part of the control system, sort of speak, and shares the infrastructure, physical cables and trays, and the same principles. From the software perspective, it is integrated in the control system (Figure 4-3).

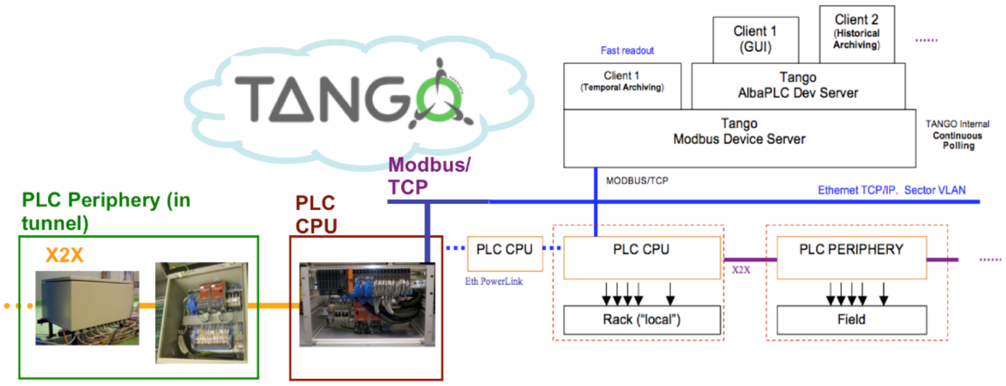


Figure 4-3: Hardware and software architecture of the Equipment Protection System at ALBA (M. Niegowski, R. Ranz, A. Rubio) [4:9].

The PSS is installed in independent trays and with independent cabling and infrastructure (Figure 4-4). It also follows specific verification, validation and certification procedures. The network is isolated and the interface with the central control system is by design read-only for diagnostics purposes.

118 PSS: Personnel Safety System.

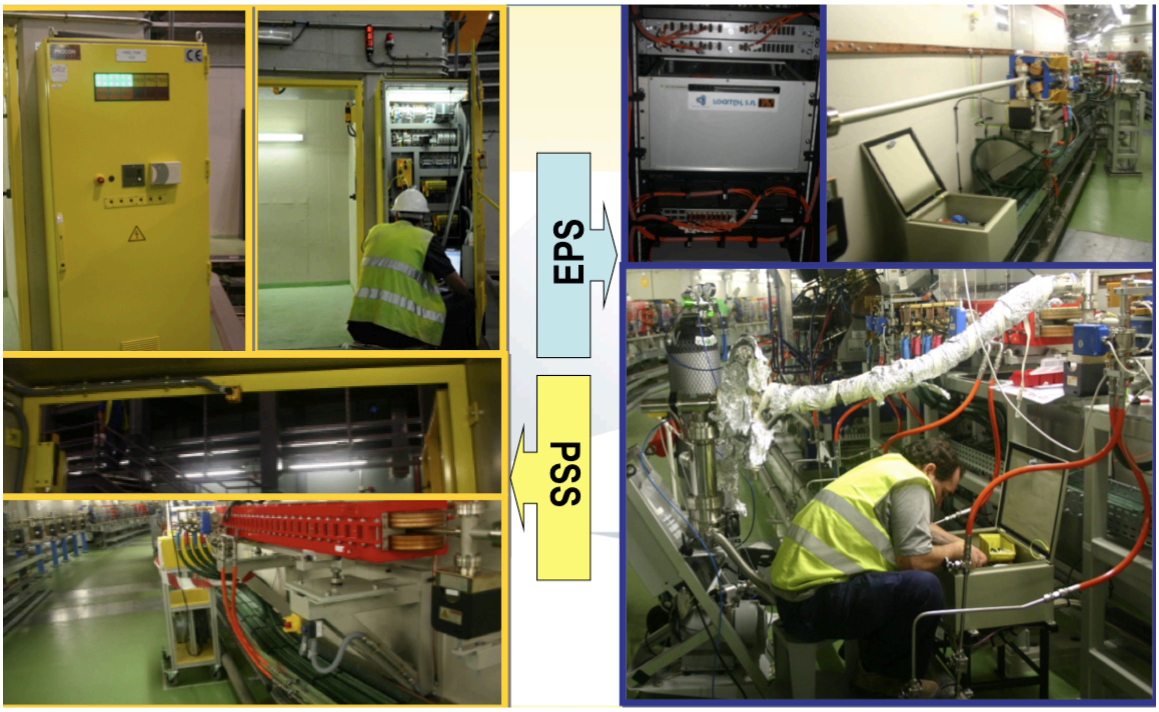


Figure 4-4: ALBA's PSS (left) and EPS (right) [4:9].

The timing system is also a transversal system that provides synchronization triggers where needed: diagnostics, power supplies, Linac, and Beamlines. It experienced a strategic upgrade to allow bidirectional communications and provide a fast interlock signals and complement the other interlock subsystems. The following paragraphs extend this conceptual design.

4.2.1 The timing system.

The timing system provides the triggering signals for the operation of the accelerators, synchronizing any diagnostic device, detector or element part of the injection process. Precisely, the Linac´s electron gun is the first triggered and all pulsed magnets and diagnostics follow accordingly, each with the precise required delay. The extraction and injection septa and kickers of transfer lines, Booster and Storage Ring, the ramped power supplies in the Booster and a number of other devices require precise triggers to work properly. There is abundant information in the literature about these processes[4:6][4:7].

The ALBA timing system is implemented with MRF[119] (Micro Research Finland) hardware, which is as of today a de-facto standard. Older machines such as the ESRF use "ad hoc" systems based on dedicated hardware to implement delays such as the DG535[120]. New

[119] MRF: Micro Research Finland. http://www.mrf.fi/
[120] Stanford Research Systems: http://www.thinksrs.com/products/DG535.htm

machines like the upgrade of the ESRF are using Ethernet PTP based systems with White Rabbit[121] technology.
The MRF system allows configuring up to 132 different events and provides 8 bits for encoding signals in this sort of distributed bus. Events are transmitted by fiber optics (typically multimode 850 nm) with 25 picoseconds RMS jitter [4:6]. The event system sends 2 bytes messages from a central event generator (cPCI-EVG230[122]), where the first bytes corresponds to the event number. Event receivers (cPCI-EVR230[123]), get all events producing an action on those each one is programmed for. The typical actions are signal outputs with a particular configured delay. The *fan-outs* (Figure 4-5) copy the event stream into several physical fiber optics to reach all event receivers at once. This process relies on length-calibrated fiber optics (200 meters is the length of the fibers of ALBA´s timing).

The timing system was initially conceived to trigger the injection[124] and diagnostics but also it can provide a fast interlock capability.

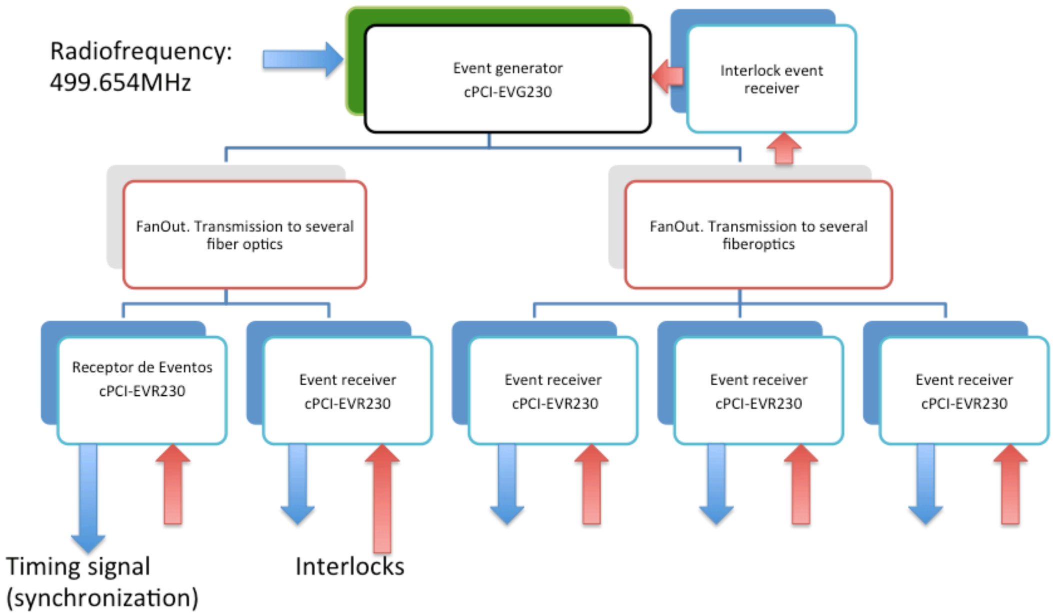


Figure 4-5: Functional diagram of the tree structure of the timing system. The bidirectional functionality represented by the red arrows was added a posteriori.

[121] The white rabbit project at the open hardware repository: https://www.ohwr.org/projects/white-rabbit
[122] cPCI-EVG230 Event Generator: Root of the tree of the timing system. http://www.mrf.fi/
[123] cPCI-EVR230 Event Receiver: They are the leaves of the tree of the timing system. http://www.mrf.fi
[124] At ALBA the injection is triggered at 3.125 Hz which means a trigger every 320 ms. This is a common value for particle accelerators. Most range from 1 to 10 Hz and in some cases reaching 100 Hz.

The injection is one of the several crucial processes that need a precise and flexible synchronization. The different filling patters[125], such as uniform, 1/3, hybrid or single bunch are besides other tunings, directly translated into different timing configurations. The radiofrequency signal and the perimeter determine the theoretical maximum number of bunches that can be injected in the Storage Ring. The number is often smaller to avoid instabilities related to a full filling.

The timing hardware infrastructure offers deterministic and fast communication links that are suitable for other functionalities, such as an interlock system. This can work in the microsecond range and is suitable for the few cases with such a high temporal requirement where the lower reliability (not fail safe) can be accepted from the safety perspective.

The machines need protection systems that in case of malfunctioning can stop the operation to protect the instrumentation. There are a large number of pieces of equipment and signals involved in these protection systems most of which do not require a fast reaction in the microsecond range. The Equipment Protection and Personnel Protection systems are managed by PLC technology, capable of handling a large number of signals geographically distributed in millisecond ranges. The extension of the timing system for handling interlocks provides a much faster mean that can transport signals from any leaf to any other in the tree in about 5 microseconds.

4.2.2 The Equipment Protection System.

The Equipment Protection System (EPS) is someway linked transversally to other subsystems and distributed across the installation. It is present in particle accelerators and Beamlines. The particular example of the ALBA synchrotron manages more than ten thousand signals in the particle accelerators organized in 49 CPUs and more than hundred remote I/O boxes[126]. All Beamlines have their own with a CPU and typically from two to four remote I/O periphery-boxes. The EPS is an integral part of the control system, although it may occasionally require dedicated infrastructure. For example, during the installation of the ALBA particle accelerators, the EPS used the standard network infrastructure for the deterministic Ethernet-PowerLink, sharing switches and fiber optics trunks configured as a dedicated VLAN. This was proven not appropriate due to the complexity of the standard switches, their optimization for bandwidth and lack of determinism. The observed latency was bigger than required (in

[125] A particle accelerator by nature and due to the radiofrequency waves do not provide continuous beams but pulsed, with a period dictated by the RF frequency. The filling pattern specifies how many and which of these buckets get particles (electrons in the case of ALBA) and how filled these bunches are.

[126] In the case of the tunnel, these are lead shielded with a communications header and a collection of input-output cards, terminal blocks and relays. These boxes are similar in the Beamlines, except that they are usually not lead shielded.

particular, deterministic networks require the latency guaranteed below a certain threshold), provoking an exception to the standard and the use of dedicated industrial switches for this purpose. Ethernet-PowerLink is an OSI level-2 network (it is not an IP-like OSI level 3), with specific provisions for deterministic latency in the switches.

In synchrotrons, the EPS controls mainly six subsystems: Vacuum, magnets, power supplies, radiofrequency plants, Insertion devices, Front-Ends and of course the Beamlines, but they can handle any signal coming from any subsystems, such as diagnostics or timing. Large installations, depending on different factors, may have independent systems with different technologies for the different subsystems. In the particular case of ALBA, the design specification was to have a single transversal equipment protection system with the same technology in order to create synergies, reduce the spare parts stocks and maintenance costs and improve the overall functionality. All subsystems are somehow interconnected through the EPS by a large variety of different signals that can be combined to create actions, permits or interlocks. For example, if the vacuum pressure raises above a threshold, the sector valves may be closed and at the same time all radiofrequency plants interlocked to stop the machine. The vacuum level is protected by closing valves and sectoring the vacuum chambers and the valves are protected from being hit by the beam by stopping (in the millisecond range) the RF high voltage power supplies and IOT amplifiers. The beam loses energy at every turn and with no RF power is completely lost in a few milliseconds.

4.2.2.1 Automatic generation of code and declaration of hardware and variables

The EPS is a large system subjected to changes and periodic maintenance, and therefore keeping the documentation up-to-date is a critical success factor. A corporate central database for the installation and the infrastructure is a strategic asset for the installation phase, for writing call for tender technical specifications to outsource cabling works to external companies; for the efficiency of the maintenance works and for keeping a centralized documentation. This central database can keep information related certain configuration of the instruments, such as the connectors, the assignment of the input/output cards to symbolic names, etc. Therefore, this central point allows the declaration of variables in the PLCs, the definition of attributes in the TANGO device servers, and even the configuration of graphical interfaces. It also allows the automatic generation of the code running in the PLCs. This offers obvious advantages and is the standard at CERN under the UNICOS framework[4:8]. In the case of ALBA, this is only partially achieved [4:9].

As an example, the Figure 4-6 shows the top-level generic EPS graphical panel for the particle accelerators of ALBA, including all subsystems states.

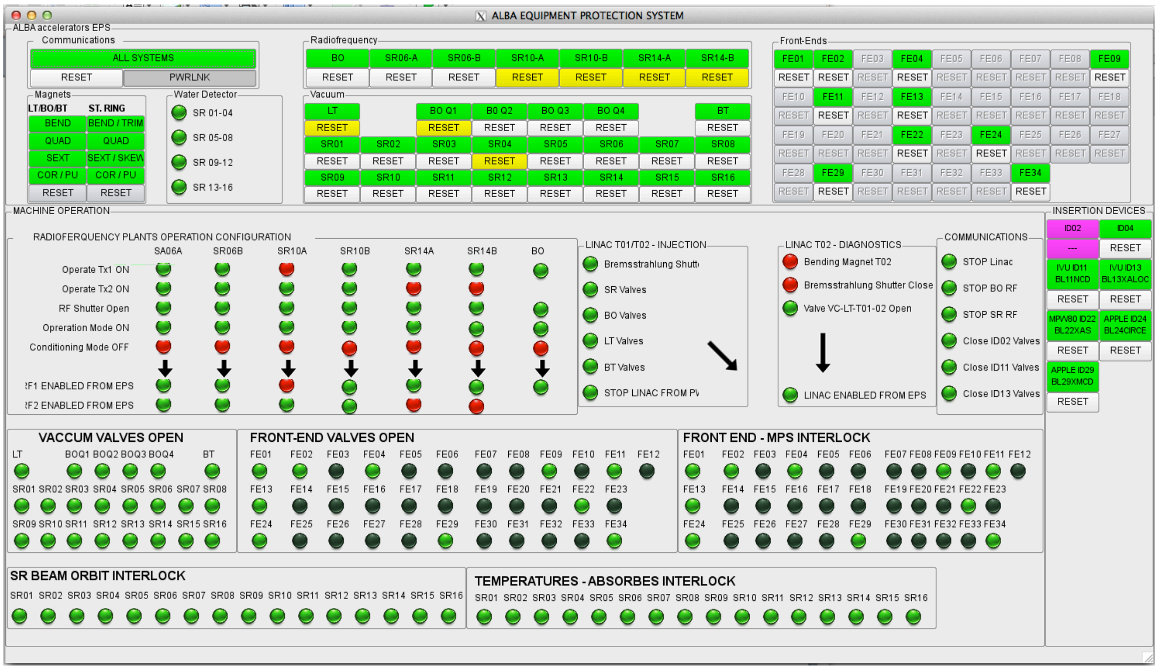


Figure 4-6: General Graphical User Interface for ALBA´s EPS [4:10].

4.2.3 The Personnel Safety Systems

The Personnel Safety System (PSS) is a critical component in all installations. In the case of particle accelerators and Beamlines, the PSS protects the people by ensuring that the radiation levels outside the shielded enclosed areas (bunkers, tunnels, lead hutches…) are below the authorized limits and that these bunkers are clear of personnel during operation. To do so, it connects to a network of radiation monitors outside the enclosed areas, implements search patrol procedures to clear these areas of personnel, and locks and controls the access doors. The particle accelerators complex and every Beamline have their own PSS. The accelerators PSS in the case of ALBA controls the access to the Linac and the tunnel by a locking mechanism with safety limit switches and a search patrol procedure with buttons defining a sequence and a proper authentication-authorization workflow. This is the same for all installations of this kind, although the number of bunkers, tunnels and doors can be different. Beamlines have lead hutches with the main optical elements, and in the case of hard X-rays Beamlines (energy ranges above 4 keV) they usually have a second lead hutch with the experimental stations, sample environments and detectors. In this case, the first optical hutch includes a photon safety shutter to prevent radiation in the second (experimental) hutch. Access to both hutches is controlled by the PSS.

The logic constitutes a series of permits and interlocks. For example, opening the photon and bremsstrahlung safety shutters in the Front End and allowing X-Rays into the optics hutch requires a permit that is made of a series of conditions (Figure 4-7).

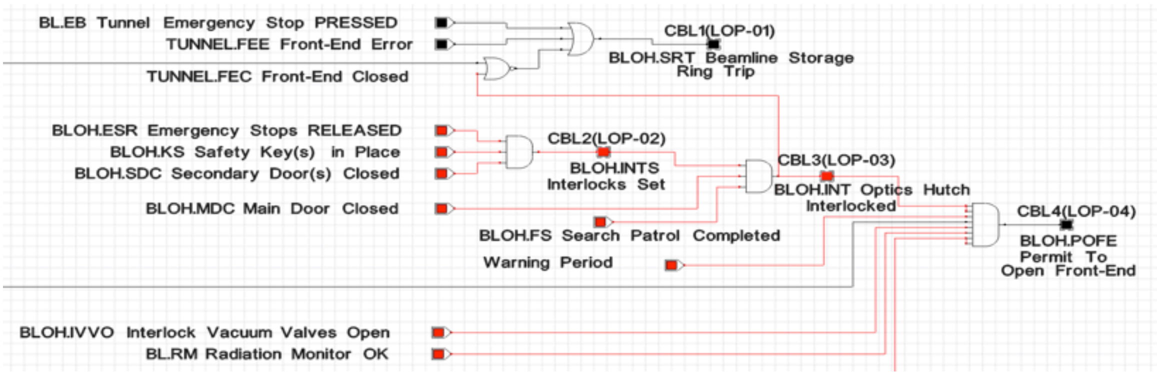


Figure 4-7: Extract of the PSS logic: Example of Front-End open permit. [4:9].

Hardware wise, older installations follow a hardwire cabling approach, like the ESRF, Diamond Light Source and many others. Nowadays the paradigm has evolved and the trend is using Safety PLCs (ALBA, designed in 2007 is based on PILZ[127] safety PLCs).

PSSs rely on the following principles (IEC-61508):

- Redundancy and diversity. Each risk shall have redundant and diverse mitigation methods. In other words, each permit, or interlock condition shall have at least 2 methods, channels, etc. and different from each other (different sensor, different manufacturer, different method, etc.)
- Permits: Revoking permits means stopping the operation if it was working or preventing it to start. A permit is associated to a certain logic that can translate to hardware in different ways, typically a safety relay (at least 2 dry contacts, with different possibilities of rearming).
- Independent from the rest of the installation both from logical and physical point of view (they are of course interconnected, by acting on the key elements of the installation by safety relays).
- Fail-Safe. Any failure shall drive the system to a safe position (mitigation of the risk triggered).
- Manual rearms. Critical systems must rearm manually after a failure. This may depend on the severity of the failure.

[127] Safety PLCs are since the nineties in the market. However, the adoption was slow. In the early 2000s there was not many manufacturers offering IEC-61580 SIL3 compatible solutions. The market was reduced to almost only Siemens and PILZ. Today in 2020, most manufacturers offer this type of solutions.

According to the norm IEC-61508 amongst others, risks are categorized in terms of severity and probability:

- Severity: Fatal, Critical, Minor, Negligible
- Probability: Probable, Occasional, Remote, Improbable

The norm IEC 61508 defines several ways to calculate the Safety Integrity Level (SIL), all difficult to apply in different cases, such as emergency shutdown events provoked by radiation monitors, due to the difficult Quantitative Risk Assessment (QRA[128]) of ionization chambers of radiation monitors.

Safety Integrity Level (SIL. IEC 61508-1)	**Probability of Failure On-Demand (PFD)**
4	10^{-5} to $< 10^{-4}$
3	10^{-4} to $< 10^{-3}$
2	10^{-3} to $< 10^{-2}$
1	10^{-2} to $< 10^{-1}$

Table 3: Failure probability and associated Safety Integrity Level (SIL). IEC-61508-1

Ideally, QRA shall be used to establish the safety requirements[129] (Table 3). Usually only the probability on demand[130] applies to PSS because it is not made of continuous automated movements but of static interlocks and permits. The complexity of the installation makes the complete graph analysis complex and in cases unworkable. A parallel solution is choosing by the experience of similar installations and selecting the Integrity Level accordingly which in practice is the highest workable. The QRA is always desirable to validate the concept.

The norm IEC-61508 defines up to six priorities, although the design of a PSS does not usually need the “high” and “incredibly-low”. The tolerance levels are given by the combination of severity and probability.

4.2.3.1 Assessment of the risks

The risk assessments usually follow the guidelines described in the norm UNE-EN ISO 14121-1:2007. A risk assessment x be carried out in different subsystems. In the case of PSSs the scope is usually restricted to the ionizing radiation hazards. In the case of light sources this risk

[128] QRA: Quantitative Risk Analysis: Obtains a probability for each risk.
[129] SIL: Safety Integrity Level: As defined in the norm IEC 61508.
[130] PFD: Probability of Failure on Demand. The device is normally stopped as opposite to continuous operation.

is related to "be accidentally exposed to ionizing radiation" where ionizing radiation can be any kind of electromagnetic radiation, such as X-rays or γ-rays (gamma radiation); or subatomic particles, such as electrons, protons, neutrons, and α-particles. In light sources these are mostly reduced to X-rays and eventually protons.

The SIL level shall be calculated in order to ensure that the PSS provides safety to meet the risk target for deaths or serious illness from radiation. This target must follow the "As Low As Reasonably Achievable" principle (ALARA), and a broadly accepted numerical value is in the order of **10^{-6}/y**, considered similar to the background level. Quantitative analyses would prove that the risk is below that limit.

A quantitative risk assessment (QRA) can be carried out by many different means[4:11], of which one extensively used is the fault tree analysis. There are number of commercially available software applications to carry out fault tree analysis[131], such as Logan, used in this proof of concept.

A Beamline gets ionizing radiation from the particle accelerators always confined in shielded hutches controlled by the PSS. The radiation levels outside the hutches are declared public, that means below 1 mSv/y (millisievert/year) or 0.5 μSv/h assuming a year equals to 2000 working hours. The PSS shall ensure that (1) nobody is inside the hutch during operation and (2) the radiation levels outside the hutch are under the limits.
The most probable hazards are identified as:

1. A trained person gains access to inside the hutch during operation.
2. A visitor (non-trained person) gets access to inside the hutch during operation.
3. Operation is started accidentally with a trained person inside.
4. Operation is started accidentally with a non-trained person (visitor) inside.

The Table 4 identifies the most important hazards in an experimental hutch, the associated probability and the PSS function for the mitigation of the risk.

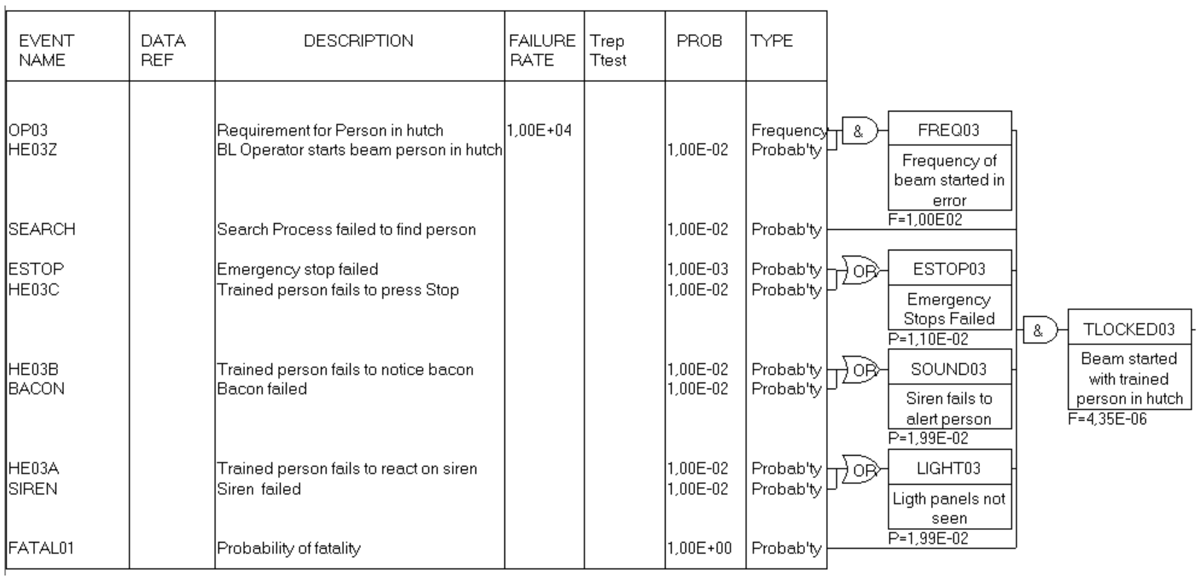
id	Hazard	Origin	Consequence	Probability of occurrence	PSS function
1.1	Exposure to radiation inside optics hutch	**Trained** person **enters** the hutch with beam on (intrusion)	Severe injury to tissues exposed	25 per day	Annunciator PSS panel Door locks and switches prevent beam entry
1.2	Exposure to radiation inside the optics hutch	**Untrained** person (Visitor) **enters** the hutch while beam on (intrusion)	Severe injury to tissues exposed	1 per week	Door locks and switches prevent beam entry
1.3	Exposure to radiation inside the optics hutch	Beam initiated while **trained** person in hutch	Severe injury to tissues exposed	2 per hour	Door locked by PSS Open door inhibits start-up Search confirmation buttons Warning acoustic siren Warning bacon Emergency stops inside and outside

[131] There are several commercial software applications to carry out fault tree analysis. One example is *Logan fault and event tree analysis* (http://loganfta.com/index.html) which was used in the example in this chapter.

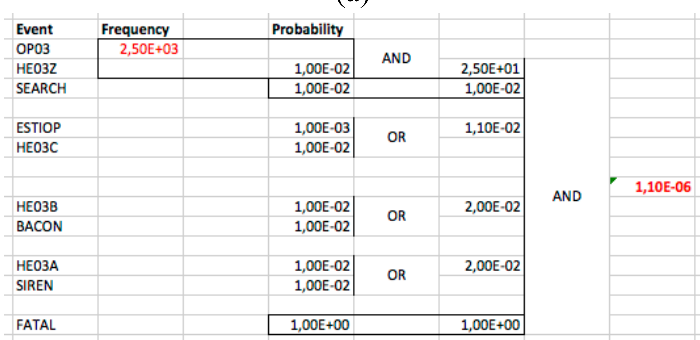
1.4	Exposure to radiation inside the optics hutch	Beam initiated while **untrained** person in hutch	Severe injury to tissues exposed	1 per week	Door locked by PSS Open door inhibits start-up Search confirmation buttons

Table 4: Preliminary risk assessment of radiation safety hazards for the PSS specification. List of identified hazards in an experimental hutch and estimated probability of occurrence.

If it is assumed that access to enclosed areas while the facility is operating will result in death i.e. a probability of fatality 1 (this is very restrictive in many cases). It is also assumed 5000 hours operation, and a frequency entering into the hutch of twice per hour (frequency, probability failure rate set to 10000). Under these assumptions, the simple fault tree would result in 4.4E-6, which does not meet requirement and would need to be refined.



(a)



(b)

Figure 4-8: FTA[132]: Beam started with a trained person inside the hutch. (a) Logan fault tree; (b)The same fault tree can be calculated with a spreadsheet: This shows the same case when dividing the frequency by 4 with the consequent affectation in the result.

[132] Using *Logan fault and event tree analysis* (http://loganfta.com/index.html)

Changing some of the assumptions, such as a frequency into the hutch from twice per hour to once every 2 hours the probability would divide by four and the result would be near the requirement (=1.1E-6. See Figure 4-8). The example shows that the quantitative assessment of risks can be very important, in particular if they are detailed which would easily result in the order of fifty trees, but it must be taken into account that they are strongly biased by the initial assumptions.

4.2.3.2 Validation of the personnel protection system (TÜV).

For an installation to comply with a determined SIL, all hardware must be chosen and installed following the standards given by that SIL. ALBA´s PSS installed a SIL3 system with PLC electronics and most components provided by PILZ.

All hardware must be installed and certified according to that SIL or greater. The system can of course include safety parts and non-safety parts which shall be properly documented. There shall be an independent verification by a different team and even from a different company performed at two different levels: (1) the verification of the elements of the hardware installation according to the standards, and (2) the verification of the functional logic and overall behavior of the system. The final certification shall be carried out by a certified company, such as *TÜV Rheinland in the case of the validation of the ALBA PSS.*

4.2.4 The fast interlock system.

PLCs offer the required flexibility in terms of programming standardization of the installation and maintenance procedures. However, there are specific cases that cannot be covered by only one standard. One very critical as described in the previous paragraphs, is the PSS that follows specific norms and regulations to perform its function. There can be others, such as the already introduced fast interlocks. There are cases whether the specified requirements cannot be easily met by a PLC based system such as the EPS. These PLC interconnect by fieldbuses and deterministic networks[133], but operate on cycles typically configured in the millisecond range (between 5 and 20 ms), which determines the minimum time between the input and the reaction output or in other words, the maximum time assigned to a task. There are specific PLC electronics to provide a fast reaction (microsecond and nanosecond range) but are not yet common in the market and are difficult to distribute through a fieldbus keeping the same constraints. Therefore, specific solutions needed to be worked out in order to meet the

[133] Reaction time guaranteed to the cycle time. In case of exception the system goes to safe state usually provoking interlocks. As an example, cycle times of ALBA EPS are between 5 and 20 ms, cycle times of ALBA PSS are about 170 ms (determined by the long distance of the Safety bus).

microsecond range interlocks required[134]. A solution is a system complementary to the EPS that can distribute signals in microseconds across several points separated hundreds of meters. This is actually provided by the Timing system as described in 4.2.1. It became bidirectional with the capability of sending specific events from any leave to the root of the tree and then back to all leaves. Later, the modification of the event receiver MRF cPCI-EVR220[135] initially developed for ALBA was standardized to all form factors and offered in the MRF catalogue to transmit and manage interlock events [4:6]. So, the fast interlock system is based on events and is built on the Timing tree structure, where the root -the event generator- gathers all interlock events generated in any of the leaves –event receivers- and retransmits the events to all the leaves at once completing the cycle in less than 5 microseconds. In other words, when an interlock signal is generated at any beam position monitor (BPM), RF plant or Front-End, is transmitted from any cPCI-EVR220 (the "leaves" of the tree, which are about a hundred units in the case of the ALBA particle accelerators) to the cPCI-EVG220[136] (the only Event Generator, the root of the tree), and from there back to all cPCI-EVR220 which can be configured to produce a particular signal output with a particular delay (or can of course ignore the event if there is nothing to interlock at its location).

In conclusion, the fast interlock system profits form the fast transmission timing system with an 8-nanosecond granularity time-stamped[137] and a 25-picosecond jitter[4:6], to conform a powerful tool to distribute fast interlocks to long distances. This system comprises typically hundreds of signals and is a complement to the much larger general purpose PLC based EPS comprising several thousands of signals.

4.3 Databases and archiving systems

Databases are essential elements in the supervision, control and data acquisition systems. TANGO based control systems require a name service, where the network references (CORBA IOR´s[138]), the device classes catalogue in device servers, device lists and device properties and attributes are stored in MySQL databases [4:12][4:13].
Archiving systems are part of the core of both industrial control systems and scientific controls. Any piece of information or particular value is candidate to be archived for future reference or

[134] Examples are interlocks of reflected power in one RF transmitter that need to interlock in a few microseconds all other RF plants distributed around the ring that can be hundreds of meters away. Other examples are orbit interlocks in any part of the ring that need to stop the beam by interlocking the RF plants and therefore avoiding the beam to hit the chamber in one particular point (interlocking the RF plants, the beam is lost homogeneously in the whole ring vacuum chamber, minimizing the damage and radiation peaks). These interlocks need to be executed in the microsecond range in order to avoid worse damages in different pieces of equipment.
[135] cPCI-EVR230 Event Receiver: The leaves of the tree in the system. http://www.mrf.fi/
[136] cPCI-EVG230 Event Generator: Root of the tree in the system. http://www.mrf.fi/
[137] Timestamps: having every event timestamped with an 8ns granularity allows a postmortem analysis, determining the source of the interlock and the succession of events afterwards.
[138] CORBA IOR: (Interoperable Object Reference)

cross-check: temperatures of vacuum chambers, beam positions, voltage and current setpoints, and in general any process variable that can be useful to later correlate data offline. The requirements are of many kinds. The sampling rates can be seconds or eventually go below milliseconds, although in the SQL archivers, rates of 30 seconds are common and enough for a large number of process variables. There can be temporal databases managing sorts of circular buffers with much faster sampling rates and a more reduced number of variables. Therefore, depending on the sampling rate a categorization in three types can be made: (1) permanent archive, (2) fast in a circular buffer (temporal) and (3) very fast on demand. The latter requires rates of micro or nanoseconds that are not convenient for SQL databases and have been implemented on purpose specific so called “fast data loggers”.

Permanent and temporal databases although both SQL may require different and dedicated instances each. In the particular case of the ALBA synchrotron, after carrying out a feasibility study it was concluded that MySQL databases (with InnoDB and MyISAM configurations) if running on the appropriate dedicated hardware, performed well enough to meet the requirements [4:14]. This was at the time unusual as most installations in operation at the time were running Oracle databases for this purpose. Initial requirements comprised between 6000 and 20000 values archived at rates slower than 10 seconds. The hardware platforms implemented dedicated computers with hundreds of GB RAM multicore processors[139] and dedicated RAID systems.

In order to increment the performance and efficiency, the process variables are archived following several schemas:

- Regular intervals: every period of seconds or minutes.
- On Change. When the readout is different from the previous one (using hysteresis intervals).
- On Thresholds: Measured value greater or smaller than a certain threshold.
- On a logic/arithmetic operation: comparison between 2 values.

The biggest challenge comes often from querying the historical databases. The response time shall be reasonable to offer a good user experience when plotting historical trend plots in human-machine interfaces. Several clients can be querying simultaneously while the database is continuously archiving data.

InnoDB tables are transaction based, with column based locking mechanisms, unlike the table based locking mechanism of MyISAM, which could upfront be an advantage but it was not the case. From experience, InnoDB tables offer a lower performance (in time) than MyISAM. However, mysql MyISAM tables have some drawbacks, such as the lack of hot backups, during data archiving. A solution would be a replication of the database, both the hardware and the software. Latest versions of MySQL already adopted InnoDB as the default.

[139] Requirements change with time. Hardware servers for archiving in the case of the Synchrotron ALBA have 132 GB RAM and 24 CPU cores (2018).

NoSQL databases are the alternative to relational SQL databases for high volumes of distributed data. Apache-Cassandra[140] is a distributed database originally designed at Facebook to manage large quantities of data on a redundant and fault tolerant way. Although it has a few disadvantages with respect to relational SQL databases (in particular limitations with complex queries), it offers many advantages in terms of scalability, availability, distribution of data and replication.

4.3.1 Fast data loggers

Some subsystems require to archive signals at microsecond or nanosecond rates and smaller: an example is the post-mortem analysis of fast feedback systems, such as the phase and amplitude regulation of the RF systems[141]. These requirements usually demand specific hardware. This is a common fact among the fast data loggers, difficult to implement with the standard archivers. They usually require archiving a reduced number of signals during a determined (reduced) period of time, usually on a trigger. This trigger can either start the acquisition or stop the acquired data on a ring buffer. The standard ADC cards[142] are in several cases suitable for these fast data loggers, working in the order of hundreds of thousand samples per second. Since they are very dependent on the system they are designed for, other dedicated hardware platforms, such as FPGAs are often used. This is the case of the ALBA´s LLRF system, implemented in specific FPGAs of the purpose specific data acquisition and regulation cards "*Lyrtech*"[4:5].

4.4 The alarm system

SCADAs provide ways to manage alarms. Alarms are a critical for the control systems because notify and register anomalous or dangerous situations from predefined conditions and values read out. These systems may acquire data from the hardware, through the network fieldbuses or from any variable in any subsystem. The conditions are evaluated on defined periods or by events and the results are notified, archived and can trigger any arbitrary combination of actions defined for that alarm.

Alarms shall have a configurable workflow:

- When an alarm is produced (the evaluation of the conditions is positive)
    - the alarm is registered
    - the alarm is notified
- The alarm is validated by the qualified/authorized operator. The validation action is independent from whether or not the conditions are still positive or the alarm

[140] Apache-Cassandra. http://www.planetcassandra.org/what-is-apache-cassandra
[141] Also known as "*Low Level RF*" o LLRF.
[142] In the case of the ALBA Synchrotron: cPCI ADLINK2005; 4 channels simultaneous sampling 16 bits ADCs

conditions are no longer met. This step makes sure the operator knows about the alarm. This manual validation would store metadata. At least:

- Date and time
- Name of the operator

If the severity of the alarm advises to do so, the alarm could also eventually be configured for an automatic acknowledge.

The notification can be carried out by different means depending on the user or group of users (loudspeaker, email, telephone text message). The reliability of the system is critical for the operation and for the general protection of the installation, although the mitigation of risks should be maximized when possible with the PLC protection systems.

In the case of ALBA, alarms are managed by TANGO device servers, implementing dynamic attributes which give the flexibility to create and manipulate existing definitions of alarms during operation [4:15][4:16]. Particles accelerators and every Beamline have their own independent alarm system (they could be combined eventually in a central alarm gathering master). Human machine interfaces allow creating online new alarms: name, preconditions and actions, visualize the active alarms, and also validate, ignore, remove or replace the configuration of these alarms.

4.5 Motor controllers and *steppermotors*

Particle accelerators require movable devices in a few systems, such as the plunger to adjust the resonance of the radiofrequency cavities, or the scrappers that can shape the beam horizontally or be used to reduce current in the beam by moving a blade in and out.

Motors are much more present in Beamlines and experimental stations. Each Beamline can have about a hundred motors (or much more depending on the configuration). Unlike the particle accelerators, that work which charged particles which are focused by magnetic fields generated by currents delivered by power supplies, the Beamlines work with photons that are typically focused by crystal polished mirrors, monochromators, slits (vertical and horizontal) etc. operated by motors.

Stepper motors are appropriate for most applications given the stability, precision, repeatability, simplicity of use and in general cost efficiency. There are several types although the most used in the shaft with a permanent magnet and a given number of teeth in the outer circle. A Pulse Width Modulator (PWM) and an alternation of phases in the teeth coils makes the axis move to the next tooth, what is referred as a *full-step*. Adjusting phases and currents they can configure movements of fraction of a step, half step or micro-stepping. Stepper motors can vary their position and keep it without an active loop on the position, in other words, they

can work in open loop, although nowadays it is common to install *encoders*[143] together with the stepper motors, so they bring more precision and stability and they make possible the closed-loop in case it is needed. Stepper motors can lose steps for various reasons, like an obstacle, imperfections in the mechanics, etc. That case can be overcome with an encoder.
When configuring half-steps or microsteps, motors are moving fractions of a step, which brings more spatial resolution to the motion, at expenses of stability and more complexity of the motor controller to regulate the current of the different phases in the middle of a natural step compromising the stability of the motor holding the position in static.

4.5.1 IcePAP

IcePAP[144][4:17] is a motor controller developed at the ESRF and optimized for high resolution applications and operation flexibility at the Beamlines. It supports four-phase stepper motors from 50 mA to 7 Amperes and several types of encoders absolutes and relatives. The form factor is 19-inch 3U chassis with up to eight axes each. They can be daisy-chained up to 128 axes in total with a master header. The system is fully configurable by software (IcePAPCMS[145]): holding and operation currents, feedback signals, encoders, closed-loops etc. IcePAP offers advanced features synchrotron oriented such as parameterized trajectories, multiple-axes synchronous movements, input-output signals to interact with triggers from the control and data acquisition systems. The interface with the control systems software is carried out by the master through Ethernet. MAXIV and Solaris equipped all their Beamlines with IcePAPs, as well as of course does the ESRF with the new Beamlines (with more than 3000 axes installed and constantly increasing).

The synchrotron ALBA has more than 600 axes distributed in all 8 operational beamlines and the accelerators. 97% of the motors at the Synchrotron ALBA are controlled by IcePAP, including the Insertion Devices. This is a great advantage in terms of usability and maintenance. There are nevertheless exceptional cases such as very high speeds requirements on heavy equipment that are solved with DC servo motors, faster but with a potentially worse performance in static positioning. Other examples of exceptions are occasional fine adjustments carried out by piezoelectric actuators[146] or picomotors[147].

---

143 Encoder: Electromechanical transducer that converts the angular or linear position in a pulse train proportional to the motion (relative encoder) or in a digital frame containing the identification of that position (absolute encoder).
144 IcePAP: Project started at the ESRF by P. Fajardo and J.M. Clement. Currently a collaboration has been formally constituted between the ESRF, ALBA and MAXIV.
145 IcePAPCMS: Configuration and test tool for IcePAP, developed at ALBA (J. Ribas, G. Cuní).
146 Piezo actuators: Based on the piezoelectric effect, under which when an electric field is applied to certain crystals it is translated to a mechanical stress and consequently a movement with resolutions in the order of picometers.
147 Picomotor: It combines the piezoelectric effect with a rotor to create picometer-resolution movements but with much higher ranges than the simple piezomotors.

Having all axes of a beamline integrated in a central system shows great advantages such as the flexibility for implementing generic continuous scans, synchronizing detectors and motions as it will be described later in this chapter. The standardization is crucial in the state of the art installations and the motor controllers in one of the most important components.

4.6 Standardization

The standardization is the key for success in several domains. Concerning the control system, the standardization is the key to embrace the total cost of ownership. This is often difficult to calculate but can be easily compared with other similar institutes. The control system of ALBA standardized operating systems, IOC chassis, PLCs, communication middleware, graphical interfaces, programming languages, version control systems for software development, repositories, configuration databases, etc. Though, it is important to note that standards must control but not forbid exceptions. Occasionally exceptions allow a much simpler and cost-effective solution at the cost of creating some extra workload in managing extra processes or maintaining stocks.

Taking the example and the learned lessons from other installations is a critical success factor. In the next paragraphs the example of ALBA control system is again used to analyze the advantages and exceptions:

- **Operating systems:** The operation started with OpenSuse 11.1 in 2009. This was the first *"evergreen"* distribution with extended support and lasted until 2020. The long-term support is important so it is to update the distribution every few years in order to maintain the system operational, secured, allow new hardware and keep the number of different versions controlled. Updating the distribution of the operating system every four or five years is reasonable, although it would depend on the new needs and on the compromises of the old versions in terms of security for example. Typically, the operators' interfaces GUI (Graphical User Interfaces) need more frequent updates than IOCs, although keeping the number of different versions reduced to the minimum is a good practice to follow. In this case, the standard can cover up to 95% of the cases, but inevitably, there will be cases which do not follow the standard due to various reasons such as commercial applications running in one particular platform or hardware (and device drivers) only supported for such platform. In the case of the control system of ALBA, about 5% of the systems use Windows OS, initially XP, then migrated to Windows 7 and later to Windows 10. Foreseeing exceptions and relying on a multiplatform control system is more cost-effective and practical than forcing the standard for 100% of the cases. Even occasionally, certain drivers are not updated to the latest versions of Windows or the migration can take much longer than planned, as it was the case migrating from 32 to 64-bit platforms. Still in 2020 with Windows 10 standardized, and 32-bit platforms at the end of life, there are certain instrumentation pieces which drivers are only available for 32-bit platforms.

At the beginning of the project, the example of existing installations such as the ESRF showed that the operating systems like OS9 running on VME platforms were very stable but had prevented the control system to incorporate new hardware for many years. The Linux versions that appeared as a consequence of that showed a lot of advantages, were more flexible and performing, but were updated too often (sometimes more than every two years) and therefore difficult to maintain in the longer run. This previous experience at the ESRF was considered at ALBA with good results.

- **Input Output Controller (IOC)** Chassis: Intel CPUs are standard. ALBA standardized the Compact PCI platforms in 2007. The VME option was at the end of life and considerably more expensive. Input-Output cards related to data collection were also standardized in order to reduce the total cost of ownership and the maintenance. The number of manufacturers was minimized to facilitate the software development and the hardware stocks. The chosen manufacturer was ADLINK, with 16bits 4-channel 500 kHz simultaneous ADCs (ADLINK2005), 2 MHz simultaneous (ADLINK2010), multiplexed ADCs, Digital-To-Analog Converters (DACs) etc. In some cases (30%), an industrial PC was chosen for economic reasons. Industrial PCs are significantly less expensive than cPCI and are perfectly fit for the purpose. Vacuum subsystems, Insertion Devices and Beamlines use industrial PCs. Diagnostics, Power Supplies, Radiofrequency, Timing and others rely on cPCI due to the form factor of the Timing Cards was only available at the time for VME and cPCI. One of the exceptions to one manufacturer is the case of the counter cards. These are extensively used by the Beamlines and are National Instruments NI6602 because the functionalities were not found in other manufacturers. Nowadays, 12 years after these choices, there are other solutions. As aforementioned a new synchrotron probably would centralize even more, would minimize the number of IOCs in the field, replaced by virtualized machines in a data center and would make much more extensively use of the deported devices and solutions based on Internet Of Things concepts. Minimizing the number of manufacturers and ensuring a long-term support resulted in a much more efficient use of the resources, sharing the same code for different device drivers and device servers, signing collaboration agreements[148] with vendors for working and improving the system. An important risk to leverage when choosing standard hardware components is ensuring a long-term support for newer software versions and avoiding the hardware discontinued after a few years.

- **Programmable Logic Controllers (PLCs)**: PLCs based systems are one of the pillars of the control system[4:10]. They are often related to protection systems, both equipment and personnel but not only. They are transversal and are linked to most

[148] And sometimes with Non-Disclosure Agreements, when the code is not Free Open Source.

systems and subsystems. The personnel Safety System was traditionally considered independent with much more restrictive requirements than other systems and excluded from the PLC world. The personnel protection systems have always been highly supervised by the local authorities and implemented with ad-hoc solutions independent from the rest of subsystems, entailing an extra cost and not necessarily a safer system. ALBA has considered the PLC technology for both the Equipment Protection System (EPS) and the Personnel Safety System (PSS). The EPS is based on B&R PLCs distributed in 60 CPUs and more than 120 remote peripheries dispersed in the accelerator complex managing more than 7000 signals and the corresponding logic. Every Beamline has also a PLC with one or more remote peripheries distributed across the hutches. The standardization of the fieldbuses is directly related with the PLCs as well. Different PLCs have better support for one or another type of deterministic fieldbus. Sometimes, the full standardization is not possible because different subsystems follow different criteria. The PSS is based on Pilz PLCs, SIL3 compatible under the norm IEC-61508. In 2006 when the design study took place, there were mainly two vendors providing the safety functionality: Siemens and Pilz. Twelve years later most PLC manufacturers have incorporated safety functions to some extent. The reason for choosing this technology and this manufacturer was the maturity of the product and the projection of the technology. At the time, the major installations did not yet trust PLCs for personnel safety. Today this has change and many institutes are already adopting the Safety PLC technology for the new upgrades and installations. These systems are usually well separated from other systems and with particular installation requirements and certification procedures. While at ALBA the EPS is an in-house development, the PSS has been outsourced to different companies involved in the installation, programming, validation and certification. The PSS has an independent installation, not only including CPUs, instrumentation and electronics, but also cables and cable trays. The maintenance of the protection systems is a critical issue, given their size and the fact that they are transversal with connections to most subsystems. Moreover, the maintenance plan has constraints -such as mandatory once a year- imposed by the competent national authorities. These systems foresee special procedures for validation of changes.
Besides the standards for the PSS and the EPS other manufacturers of PLCs coexist in the installation; Siemens in most cases, but also, Allen-Bradley or Phoenix Contact, often imposed by turn-key systems such as the Linac, high voltage power supplies, radiofrequency systems, etc.

- **Ethernet is the main communication channel** for corporate networks, supervision, control and data acquisition at all levels, including also **fieldbuses**. Segmentation strategies, network virtualization and firewalls have been deployed keeping the security standards and also with the goal of optimizing the performance. Standardizing Ethernet

makes the installation more cost-effective, keeps the ownership cost controlled and makes the maintenance easier. This evolves into a sort of Internet-of-Things approach where Ethernet (and TCP/IP) is the main bus with various physical layers ranging from fiber optics, copper cables or wireless. However, there are cases where forcing a subsystem to the follow the standard would mean a higher cost or a lower performance. This is the case of the deterministic network Ethernet-PowerLink that connects the CPUs of the EPS PLCs, ensuring cycle times of 20ms (user defined). The standard switches were designed to maximize data throughput but not minimizing the latency. This causes the determinism to fail. The solution is to take this network off the corporate network and install dedicated small industrial switches for this particular purpose. Other exceptions were the communication with the correctors power supplies of the Storage Ring (176 in total), which did not use Ethernet as the rest of the power supplies but a specific connection in order to assure the fast rate (5-10 kHz) needed by the fast orbit feedback. This configuration is innovative and unusual. Years ago, the most common feedback was local, involving only a few monitors and correctors, or global but at much lower sampling rates. Since more than ten years, contributed by "de facto" standardization of the Libera boxes, the 10 KHz feedback systems became the norm, with algorithms and actuators implemented on FPGAs. The innovation comes from the evolution of CPUs and operating systems. A specific configuration of the regular Linux Kernel, running on 4-core CPU with a specific assignment of processes to CPU-cores makes the execution of correction algorithms in a regular CPUs possible (in the current case of ALBA this is at the cost of dividing the frequency by two, that is 5 kHz which is still good for correcting instabilities up to 100 Hz).
Exceptions may also be required due to installation costs. This is the case of the vacuum systems where the communication with ionic pumps and gauge controllers rely on serial lines instead of Ethernet. The choice was made because of serial lines being much more economic than Ethernet at the time for the several hundreds of units distributed across the installation.

- **Motor Controller**: Beamlines may have in average about hundred motors. This depends very much on the Beamlines, with the newer ones installed at the ESRF reaching more than 300, and the smaller ones having a few tens of them. This number is continuously growing in both cases of existing and newly designed Beamlines. A standardized motor control system, allowing to synchronize the movement of various axes, send/receive synchronization signals based on position, manage complex trajectories involving different motors in the Beamline is today a great competitive advantage and in the short future it will be a must. The market offers a wide range of vendors and models that can do the job to some extend but may not be flexible enough to incorporate new functionalities. Besides, standardizing one commercial model for all applications has obvious advantages but is not very cost effective. The ESRF developed the IcePAP system[4:17] following the requirements given by the Beamlines and foreseen for the future. ALBA joined later, standardizing the whole installation with this paradigm from the design phase including accelerators, Insertion Devices and Beamlines. This is a key feature for the standardization of the continuous *scans* as the standard data acquisition technique discussed in the following paragraphs of this chapter.

- **Corporate installation and cabling database**: Within the context of configuration items and asset management, the development of a database for the installation, cabling, instrumentation and electronics has proven to be an important competitive advantage;
    - it speeds up the call for tender's process for the cabling manufacturing and installation,
    - it keeps the documentation up-to-date,
    - it enforces standard procedures for installation and ensures the compliance with these procedures,
    - it improves the quality of the installation process and helps reducing the number of mistakes and human errors.
    - it introduces a certain configuration management, although not yet at the level of a Product Lifecycle Management (PLM) system.

  In some cases, when a certain equipment is installed as turn-key, the instrumentation, cabling and documentation is not included in the database and is treated as an exception. This made easier certain tenders, although when the warranty expires, it often becomes a problem, and therefore most of these exceptions need to be reconsidered. Having such as corporate database plays also an important role in the maintenance procedures, keeping a centralized track of the failures and controlling the stocks.

This is not an exhaustive list. There are many standards to consider when undertaking a project of the magnitude of building a large scientific installation. The ones above mentioned represented in a way or another a kind of innovation for the time. There are many other considerations to make when designing a large infrastructure to operate for several decades, which are not listed here. In the domain of control system software, examples are: naming conventions for equipment, instrumentation and computers, coding standards, the version control, continuous integration and continuous delivery, among others.

4.7 **The evolution of the scientific control systems. Sardana and scientific SCADAS for experimental stations**.

TANGO offers the ecosystem with a middleware to implement distributed control systems following the client-server model. This ecosystem includes the tools for the development and management of the whole system. However, neither TANGO nor EPICS offer the development environment and an advance support to create workflows, macros and sequences to perform an arbitrary experiment. Beamlines have new users with a new experiments and new requirements arriving every week or less. Every experiment has different requirements and may require different hardware and different software solutions. Sardana like SPEC, offers a development and macro execution environment, an advanced command line interface, graphical interfaces and an optimized access to the hardware from a centralized orchestrator.

Sardana was proposed at ALBA in 2005 by J. Klora who drafted the initial requirements. It was first prototyped by E. Taurel and T. Coutinho [4:18]. Years later (2013) the work was internationalized and extended to collaborations with MAXIV, DESY and Solaris, although ALBA still plays a central role in the development and support; in particular Z. Reszela, G. Cuní, C. Pascual and all members of the controls Team [4:19].

Sardana is a sort of SCADA for accelerators and Beamlines, which provides graphical interfaces, command line interfaces, macro execution environments, interfaces with archiving, etc. It is written in Python and has a number of core components (Figure 4-10) such as the most important:

- A core, in a form of a TANGO device server in the current version, which comprises the controllers and different elements of the system. The core optimizes the access to the hardware and provides an abstraction layer to functionalities of different elements. The model conceives movable devices (motors and equivalents) and acquirable devices, such as counters, detectors and in general any hardware that offers data to acquire. Like SPEC, controllers comprise different devices and elements often controlled by a single piece of hardware. This is name as "Device Pool".
- The second element provides a macro and sequence execution environment. It is the direct complement of the Device Pool, also a TANGO device that can be in the same or in a different server and is referred to as MacroServer. This device loads and executes macros and sequences. Macros are reusable procedures with access to the hardware, that run in a controlled environment and with interfaces with graphical and command line interface tools. The most used and the best example of a macro is the ″scan″[149]. The Sardana macros are written in Python whilst SPEC´s are written in a C-like specific interpreted language. Both have a standard macro library, defining absolute scans (ascan) relative scans (dscan), combination of motions (a2scan) etc. The fact that the macros mimic the SPEC syntax - de-facto standard – simplifies the learning curve. An ascan performs a sequence of movements with any movable/scannable element from an origin to a final position combined with a series of acquisitions with all the preconfigured elements performed at each interval. Generically, any arbitrary combination of movable axes and detectors can be configured to participate in a scan.

[149] **scan**. A scan is a sequence of movements and data acquisition. A motor or an arbitrary combination of motors and pseudomotors move following a trajectory and at certain intervals the system acquires data from a combination of synchronous detectors and sensors. The traditional scan (step scan) stops the motion of the intervening axes to acquire data and then restart until the next interval. The continuous scan does not stop the motion to perform synchronous triggered data acquisition.

- *Spock* is the command line interface based in ipython that allows to execute macros, or functions, access objects, manage the history of commands, etc. Again, the look and feel was standardized and popularized by SPEC in the nineties and it carried on until nowadays (Figure 4-9).

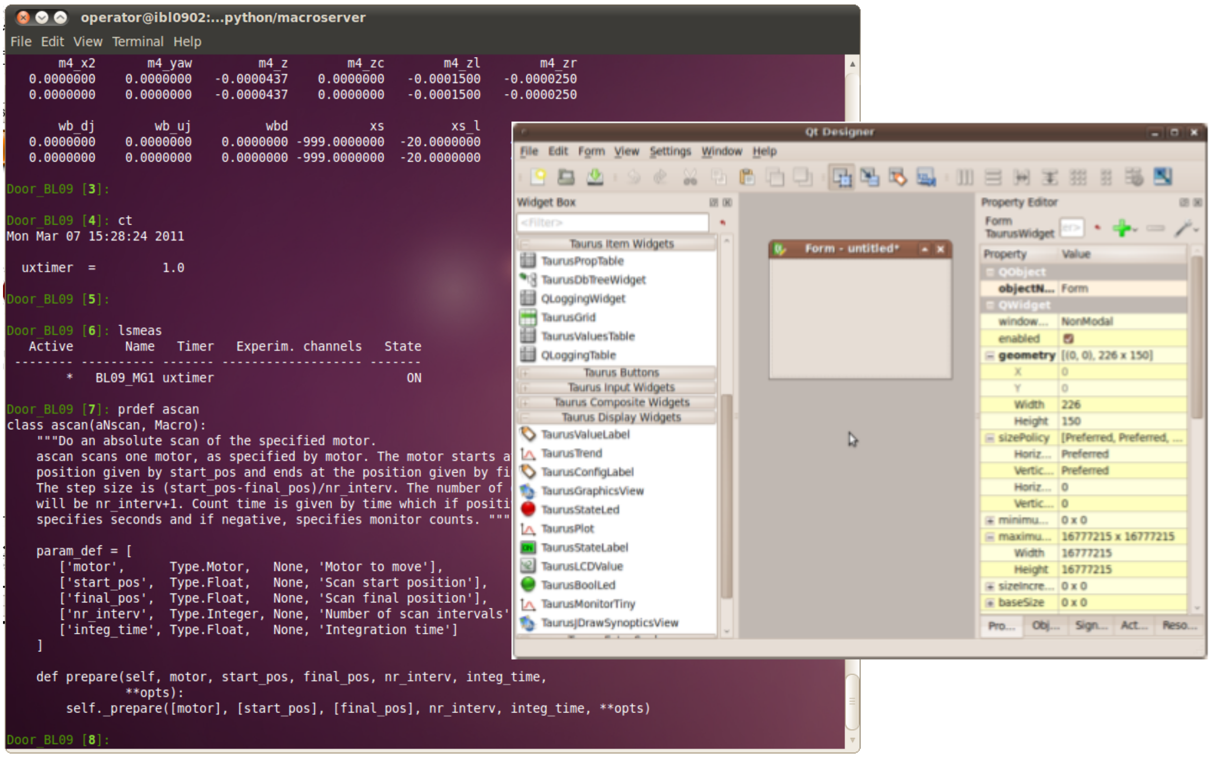


Figure 4-9: Left: SPOCK, the command line interface inspired in the SPEC library and macro environment. Right: Qt Designer (Qt Company Ltd©), customized with Sardana/Taurus widgets [4:18]

- Taurus was developed in the context of the Sardana project for the provision of graphical interfaces based in PyQt, following the Model-View-Controller (MVC). It later evolved to a scheme based architecture to give access to various data sources, such as EPICS, TANGO or others. It is today very popular amongst the TANGO community. The Taurus project[4:20] also offers a graphical tool called TaurusGUI[4:21] to create graphical user interfaces without programming. The widget library can also be extended and integrated in the Qt "*Designer*" (Figure 4-9 left).

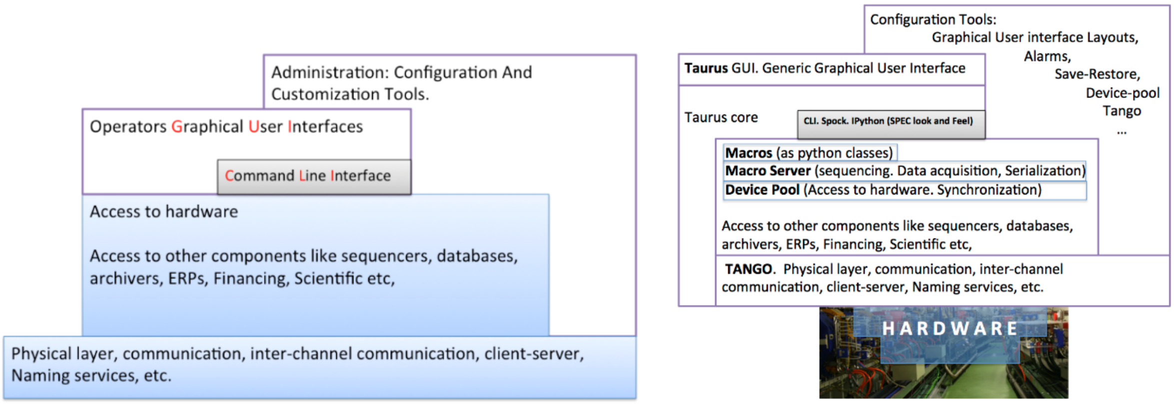


Figure 4-10: Left: Generic requirements of a scientific installation SCADA system. Right: Overview of the architecture of the control system of the ALBA synchrotron.

Data acquisition processes, in particular motion related scans such as slits, mirrors, diffractometers, etc. require reduced latencies, overheads and deadtimes to increase the acquisition speed. Newer experiments have such time-constraints that depend on this optimization to succeed. Detectors are getting faster and the readout is more efficient. In order to overcome the software and motion overheads, the solution are the continuous scans (also known as fly-scans, quick-scans…). The technique is open to numerous synchronization possibilities. The synchronization is often carried out by a trigger signal generated by an electronic board getting inputs from various other signals such as encoder pulses. This is a common scenario, where certain preconfigured positions (encoder pulses) trigger the acquisition at given points. Therefore, a generic continuous scanning solution requires a centralized management of motors and encoders.

SCADAs are to provide generic solutions for the different scenarios present at the Beamline. This means integrating different motor manufacturers; offering software abstraction layers to build logical motors (pseudomotors) as a combination of any kind of axes and integrating fast and large area detectors as well as scalars and vector-like detectors by providing buffering, synchronization and online visualization. Figure 4-11 shows an example of configuration facilities for 2-dimensional detectors (CCD area detector).

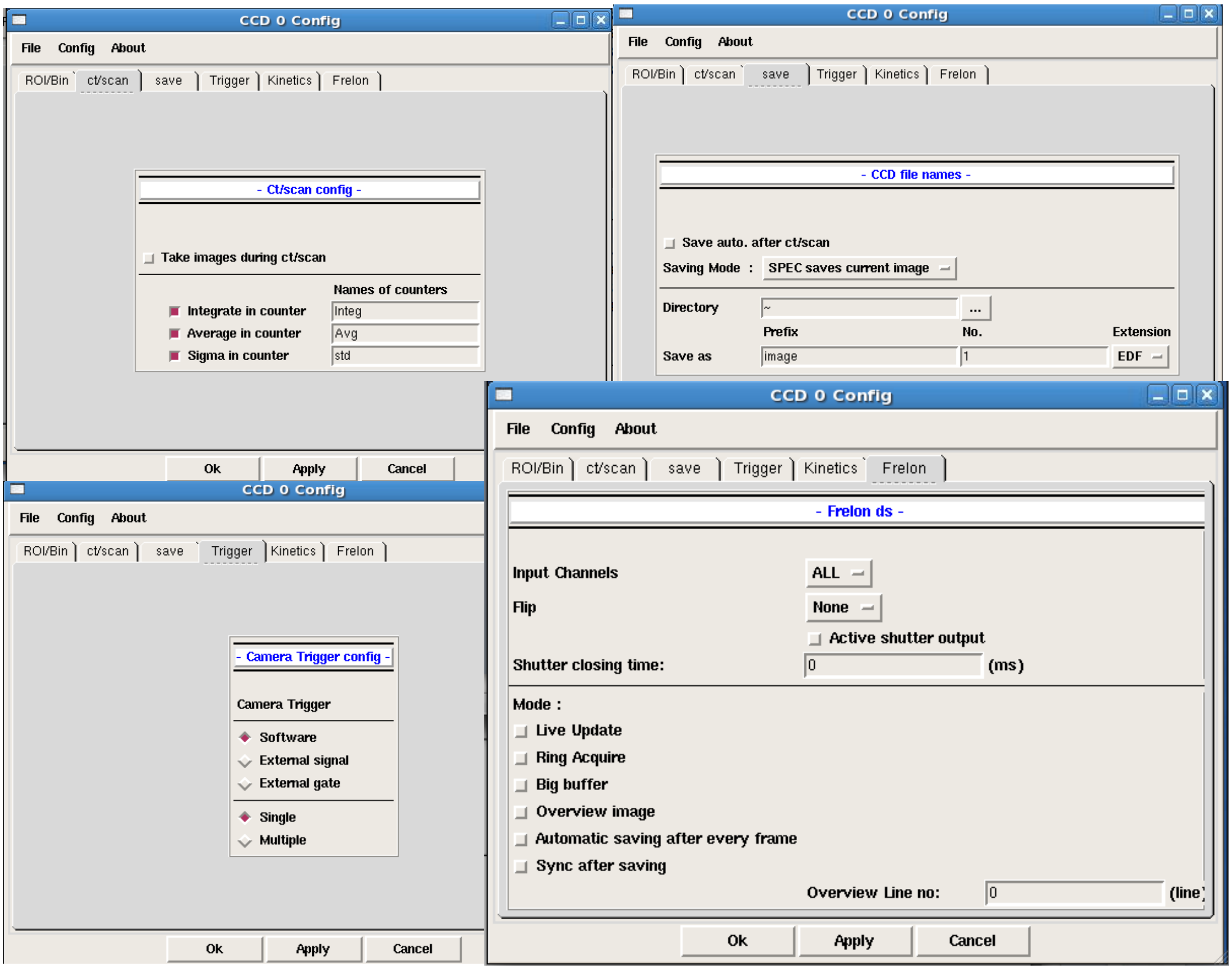


Figure 4-11: Configuration Requirements for 2D detectors data acquisition at the Beamlines´ experimental stations.

Figure 4-12 shows a graphical user interface for a detector data acquisition system implemented with SPEC (FReLoN CCD camera [4:22]).

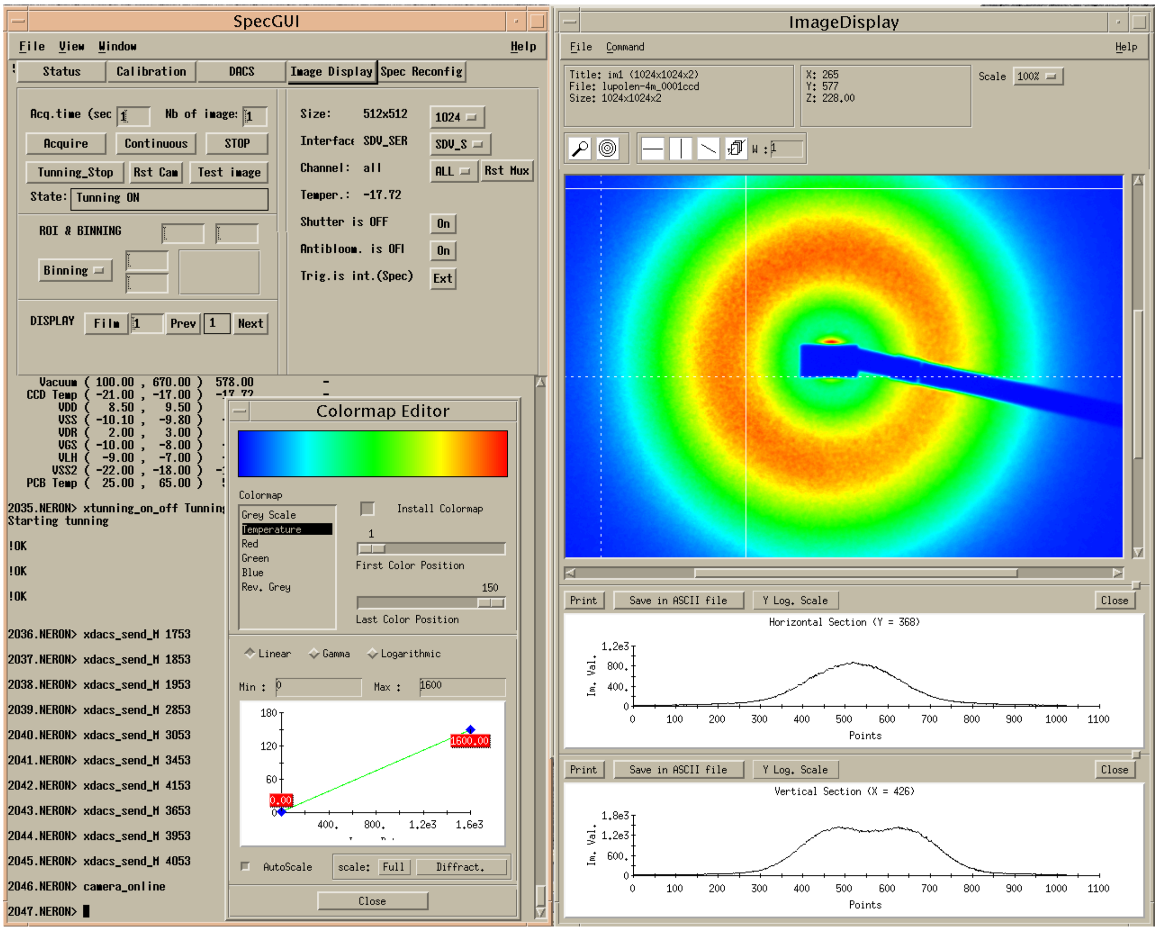


Figure 4-12: Data acquisition interface for a 2D detector built with SPEC and SPECGUI (CCD FReLoN camera, ESRF) [4:22].

4.8 Advanced requirements for Beamlines and experimental stations

The capacity of executing scans or any other type of macros and sequences in a beamline is crucial for the operation. Mono and multi-motor scans are commonly used for alignment procedures and the experiment itself. Arbitrary combination of motors (amongst the more than a hundred a Beamline can have) and detectors and experimental channels intervene in these scans. Therefore, the user-friendliness and flexibility for configuring the experiments is a critical success factor and so it is the visualization and plotting of the different scalars with the motor positions and online processing of large area detectors. The channels that take part of the measurements must be easily added and removed from the configuration interface. Every channel shall have a conceptual time-base (timer) associated to it, that specifies how the synchronization of the channel will be performed with respect to the rest of the channels intervening in the acquisition.

The triggering can be:

- *Software*, when the acquisition of that channel is started by a software command.
- *External_Trigger*, when that channel has a piece of electronics associated that is triggered by an external pulse.
- *External_Gate*, when the electronics responds to an external pulse, being the length of the pulse the acquisition (exposure) time.

All trigger modes can be either single or multiple. Single, the usual case, means that the acquisition is done once. Occasionally, several acquisitions (exposures) can be taken at the same point and can be triggered with a multiple trigger. In addition, there are of course a lot of parameters that can be configured and tuned regarding the plotting, curve colors, normalizations, etc. The Figure 4-13 shows a basic configuration schema for the experimental channels.

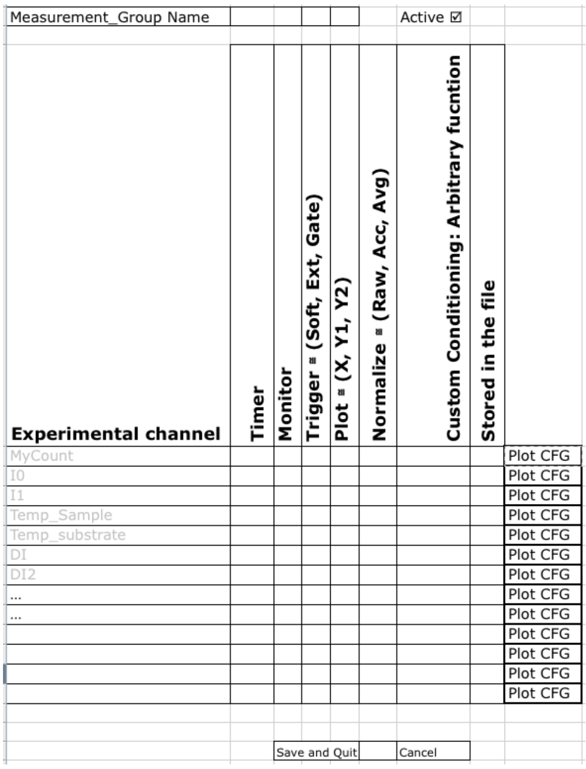


Figure 4-13. Configuration requirements of the different elements that can take part in a scan.

Many detector types can be part of an experiment: scalars, one-dimensional (1D), two-dimensional (2D). Each with particular characteristics and dedicated electronics adapted to specific experiments. The scientific SCADA must handle such variety of hardware and interfaces and provide the abstraction needed to reuse the maximum number of sequences, macros, data files and data acquisition procedures. Other data acquisition standards can be

implemented by default, such as a reference counter to normalize with (I_0) or acting as a monitor scalar to stop the acquisition when reaching a predefined threshold.
1D and 2D detectors can equally define regions of interest (RoI) and data pre-processed intermediate results, such as pseudo-counters (for example as the result of the integration of a region of interest), average, sigma, median, etc. These standard preprocessing tools can also include dark images for 2D detectors that can be then subtracted from the images acquired during the experiment in order to remove the background, or flat field images to normalize with (see chapter 5). This flexibility to configure the graphical plots, archiving, synchronization and arbitrary experimental channels in general, is another critical success factor for a scientific SCADA.

4.8.1 Movements. Movable or *scannable* elements

Most experiments require combined motion of several axes and acquire data during that movement. Data acquisition can take place step by step, stopping the motion at each step or in continuous mode, that is acquiring during the movement. Motion can be of one single axis or complex with several motors or of virtual axes (pseudomotors). Programing these pseudomotors can be complex given the fact that as aforementioned *movables* can combine physical motors with other virtual axes of different nature, such as temperatures, power supplies, laser instruments, etc.

4.8.2 Detectors and monitors. Experimental channels.

Process variables and experimental channels can have several dimensions: scalars, vectors of one dimension such as the results of a Multi-Channel Analyzer (MCA), 2 dimensions (for example images from a CCD camera) and of N dimensions in general. Scalers are always present as diagnostics or monitors for further normalization and can be incorporated to the data acquisition process of a scan. A data acquisition starts monitors and detectors with a preset exposure time which are often synchronized by an external signal. The channels that are not synchronized by the external signal will most probably observe a jitter in the absolute time (which shall be time-stamped if possible). Shutters are key elements to mitigate this jitter when synchronizing different detectors and experimental channels. Software channels are pre-started and read out after the acquisition is completed (in the case they are integrators) and the shutter is closed.

The timestamp shall be associated to each channel and each datum. The timestamp shall be as accurate as possible (in the microsecond range for exposure times of several milliseconds). This is one of the important challenges to solve in the continuous improvement cycle of the data acquisition process that constantly increases speed, flexibility and accuracy. When the data acquisition is synchronized by hardware, the exposure time is tightly controlled and therefore timestamps are not so critical, since are all linked to the timestamp of the synchronizer. The precision of the synchronization is often at least as good as the accuracy of the timestamp.

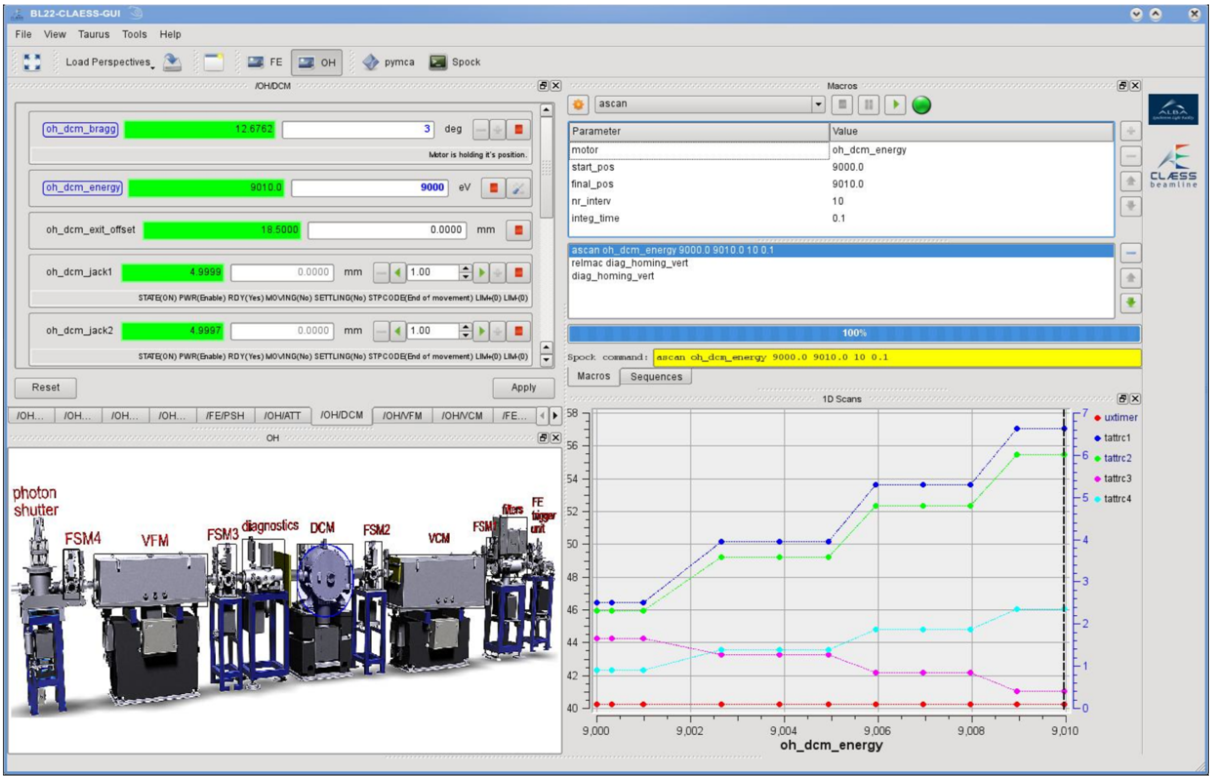


Figure 4-14: Sardana Graphical User Interface PyQt based created with con TaurusGUI for BL22-CLAESS at ALBA Synchrotron. Different widget types are trends charts (down-right), synoptic (down left), macro configuration and execution (top right) and generic form (top left). Z. Reszela et al. [4:18][4:19].

4.8.3 Visualization and data storage

The graphs for the visualization are chosen according to the data types. The most common is the trend graph, which represents magnitudes of scalars (counters) in the vertical axis and motor positions in the horizontal axis (Figure 4-14). Once the data acquisition is configured with all participating detectors, both visualization and archiving can be selected and configured (SPEC files: Figure 4-15, NeXus/HDF5: Figure 4-16, amongst others). When detectors have one or two dimensions the view is often an image display that updates the image or concatenates the succession of vectors in time. However, when data sizes and acquisition speeds increase, the visualization requires more resources, memory, computing power, etc. and needs optimization. Moreover, in some cases humans neither need nor want to check on every piece of data (a camera acquiring at 100 frames per second rates will probably need to store all data, but probably does not need to display 100 frames per second). The optimization happens at different levels. The detector (1) handles a buffer with a number of frames; (2) data can be compressed or streamed directly to the disk cabins (NAS[150] or clustered-NAS parallel implementations such as GPFS from IBM or OneFS from EMC-Ipsilon/DELL, Lustre with HPE/Cray systems amongst others). Typically, a combination of both decimation/preprocessing and fast streaming to the disks is the best option to ensure the quality of the datasets. On-line visualization is important to have, but with the right optimization and prioritization, with the right assignment of resources for the human interaction.

The data storage is always a critical issue. Ideally, this will be a single repository with a full consistent metadata, and with datasets interoperable across different facilities. Data catalogues will be available, public, open access and free. However, although this is the strategy of the European Commission, fostered by the FAIR[151] principles, it is still a long term and ambitious project. The goal is challenging and difficult and requires managing a data format to include such a large variety of techniques in so many different installations. The data format as well as the metadata definitions shall be agreed, in order to achieve interoperability. The most advanced prototype in photon and neutron sources is the NeXus file format (*Neutron and X-Ray common data format*)[152], and more particularly the HDF5 implementation. Nexus is built on HDF5 and XML[153]. Nexus and HDF5 allow storing large and complex datasets including different detectors in a single file, although issues such as high data rates from detectors writing into files simultaneously with read operations by other clients, and the harmonization of the metadata and application definitions need still to be solved.

Independent files for every image from large detectors are still the norm in many installations. To ensure the traceability and consistency of the datasets, central mounted repositories NFS[154] are a good alternative. These shall be combined with parallel file systems such as GPFS or OneFS to achieve the required performance of up to a several GB/s in some cases. Having central repositories is also key for managing backups, archives, and the consistency of metadata and datasets, as well as for data processing. Results of the data processing can also be included in these data sets for further references.

---

[150] Network Attached Storage systems. Data storage systems connected to the network for a wide number of clients. https://en.wikipedia.org/wiki/Network-attached_storage

[151] FAIR: Findable, Accessible, Interoperable and Reusable. The European Commission under its H2020 framework program published guidelines for beneficiaries to make their research open (FAIR).

[152] NeXuS scientific data format: http://www.nexusformat.org

[153] XML: Extended Markup Language

[154] NFS: Network File System

```
#S 39  mesh xmcd_z 20000.0 -10000.0 300 xmcd_x -10000.0 20000.0 15 0.1
#D Sun Jul  1 15:55:23 2012
#T 0.1  (seconds)
#P0  -314.947289157 51.25 284.169861 300.0 15.0 0.0 19996.9992498 1700.0 36000.0 1000.0 -1155.0 30000.0 576.25 1
.8 135676.0 105.0 750.0 130413.9 1054.0 2940.0 215.0 177.5 750.0 1000.0 300.0 -32000.0 285.0 10.0 8100.187 1200.
271637 -4969.33045356 102212.2 0.0 -2051.0 102118.0 1800.0 0.0 -63149.8127341 225.736095965 -6367.82902137 0.0 1
#N  13
#L   xmcd_z  Pt_No  xmcd_x  adc1_i1  adc1_i2  adc1_i3  adc1_i4  adc1_timer  energy_mono_avg  gr_pitch_ren1_enc
 19999.96 -10000.0 0 -0.000765747070312 -1.53442932129 -0.00172387695312 1.35119622803 0.1 637.300293106 498336.
 19899.884 -10000.0 1 -0.000759582519531 -1.51762750244 -0.00189215087891 1.35059875488 0.1 637.300293106 498336
 19799.935 -10000.0 2 -0.0007626953125 -1.52844616699 -0.00269744873047 1.34964697266 0.1 637.300293106 498337.3
```

Figure 4-15: SPEC file. Only ASCII, although one could also link binary files.

```
dfernandez@controls01:~/tmp> h5dump my.h5
HDF5 "my.h5" {
GROUP "/" {
  ATTRIBUTE "HDF5_Version" {
    DATATYPE  H5T_STRING {
        STRSIZE 5;
        STRPAD H5T_STR_NULLTERM;
        CSET H5T_CSET_ASCII;
        CTYPE H5T_C_S1;
      }
    DATASPACE  SCALAR
    DATA {
    (0): "1.8.1"
  ATTRIBUTE "NeXus_version" {
    DATATYPE  H5T_STRING {
        STRSIZE 5;
        STRPAD H5T_STR_NULLTERM;
        CSET H5T_CSET_ASCII;
        CTYPE H5T_C_S1;
    }
    DATASPACE  SCALAR
    DATA {
    (0): "4.3.0"
  ATTRIBUTE "file_name" {
    DATATYPE  H5T_STRING {
        STRSIZE 60;
        STRPAD H5T_STR_NULLTERM;
        CSET H5T_CSET_ASCII;
        CTYPE H5T_C_S1;
      }
    DATASPACE  SCALAR
    DATA {
    (0): "scanfile20120701.h5"
  ATTRIBUTE "file_time" {
    DATATYPE  H5T_STRING {
        STRSIZE 25;
        STRPAD H5T_STR_NULLTERM;
        CSET H5T_CSET_ASCII;
        CTYPE H5T_C_S1;
    DATASPACE  SCALAR
    DATA {
    (0): "2012-07-01T10:24:58+01:00"
  GROUP "entry1" {
    ATTRIBUTE "NX_class" {
      DATATYPE  H5T_STRING {
          STRSIZE 7;
          STRPAD H5T_STR_NULLTERM;
          CSET H5T_CSET_ASCII;
          CTYPE H5T_C_S1;
        }
      DATASPACE  SCALAR
      DATA {
      (0): "NXentry"
    ATTRIBUTE "epoch" {
      DATATYPE  H5T_IEEE_F64LE
      DATASPACE  SCALAR
      DATA {
      (0): 1.34113e+09
    DATASET "definition" {
      DATATYPE  H5T_STRING {
          STRSIZE 6;
          STRPAD H5T_STR_NULLTERM;
          CSET H5T_CSET_ASCII;
          CTYPE H5T_C_S1;
      DATASPACE  SIMPLE { ( 1 ) / ( 1 ) }
      DATA {
      (0): "NXscan"
    DATASET "entry_identifier" {
      DATATYPE  H5T_STRING {
          STRSIZE 1;
          STRPAD H5T_STR_NULLTERM;
          CSET H5T_CSET_ASCII;
          CTYPE H5T_C_S1;
      DATASPACE  SIMPLE { ( 1 ) / ( 1 ) }
      DATA {
      (0): "1"
    GROUP "measurement" {
      ATTRIBUTE "NX_class" {
        DATATYPE  H5T_STRING {
            STRSIZE 12;
            STRPAD H5T_STR_NULLTERM;
            CSET H5T_CSET_ASCII;
            CTYPE H5T_C_S1;
          }
        DATASPACE  SCALAR
        DATA {
        (0): "NXcollection"
      DATASET "Pt_No" {
        DATATYPE  H5T_STD_I64LE
        DATASPACE  SIMPLE { ( 49 ) / ( H5S_UNLIMITED ) }
        DATA {
        (0): 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,
        (17): 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31,
        (32): 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46,
        (47): 47, 48
      DATASET "adc1_i1" {
        DATATYPE  H5T_IEEE_F64LE
        DATASPACE  SIMPLE { ( 49 ) / ( H5S_UNLIMITED ) }
        DATA {
        (0): -0.000747742, -0.000761597, -0.000761841, -
0.000778687,
        (4): -0.000750488, -0.000764771, -0.000757629, -
0.000759949,
        (8): -0.000762939, -0.000756287, -0.000766663, -
0.000758972,
(…)
```

Figure 4-16: NeXuS file (HDF5 converted to ASCII). It allows metadata and links to external files. It also stores binary data such as images.

4.8.4 Continuous scans

Every control and data acquisition system has the challenge to speed up the process. The experimental station of a synchrotron scans movable objects taking measurements in intervals as the main data acquisition process. Traditional scans move the combination of axes in intervals and make measurements at these intervals with the motion stopped. The measures can involve any combination of detectors. Therefore, to optimize the process, is important to minimize the overheads between the motion and the acquisition, given by the software synchronization of the different elements distributed across the network (state checks and start/stop commands). These aforementioned step scans are very flexible and necessary for certain operations. However, the requirements of the experiments constantly evolve and go often a step ahead the technology, pushing the limits of the instrumentation and data acquisition system capabilities. In order to meet these requirements and speedup the process it is necessary to take measurements during the movement, without stopping the axes involved in the experiment. This could benefit also the quality of the data under certain conditions, as the acquisition covers a larger solid angle. These are known as continuous scans, quick scans or flyscans in certain literature [4:23][4:24]. A continuous scan can also involve one or more axes and complex trajectories. There must be a motion master and a synchronization mechanism for the detectors and readout channels. The ultimate requirement for the synchronization and the quality of the data analysis is that all readouts have a precise absolute timestamp. Data analysis strongly depends on each particular technique, but algorithms often require having data for all configured channels at each point.

The synchronization offers several possibilities: triggering at given positions of an axis or at estimated time intervals. This external trigger is managed by a synchronization element that computes the position of an axis from an encoder signal (for example incremental quadrature or absolute) and generates triggers for all elements to be read at these given positions. These elements include counters, electrometers, cameras and other 1D and 2D detectors. The speed of the axis is calculated from the number of intervals and the exposure time, taking into account both software and readout overheads. The acceleration and deceleration of the movement is also taken into account to calculate the starting and stopping positions and to manage the axes´ limits.

A generic approximation requires covering all singularities of experimental channels. There can be motors that cannot be synchronized by position and which would require a synchronization by time intervals. The axis to synchronize can be virtual (formed by several axes). These cases are known in the synchrotron jargon as pseudomotors. Pseudomotors can be composed of several physical axes; for example, the height of a table depends of the height of all legs, although there could depend of only one, for example the energy given by a monochromator (in eV) may be calculated from an angle of a motorized axis (in mrad or degrees). Pseudomotors bring more complexity to continuous scans because the parameters of all motors involved in that particular virtual axis shall be managed (speeds, accelerations, motion limits, etc.). Let's take a simple pseudomotor, such as 3-leg table. These are widely used to install optical elements in a Beamline, such as mirrors. Most common pseudomotors are *"height"* (z), which is calculated from the height of the 3 legs, the longitudinal angle "*pitch*", and the transversal angle "*roll*". Depending on the configuration, these motions require moving 2 or 3 axes simultaneously. The pre-configuration of the continuous scans shall verify the limits of all axes and adjust the speeds and accelerations for them to start and stop synchronously at the right position.

The continuous scan shall be intuitive, or in other words, shall be defined the closest possible to the traditional step scan to make the learning curve easier for the users. In other words, it should look as close as possible to the step scan. This requires fundamental changes in the data acquisition processes. The first change comes from detectors that shall be synchronized with a master axis and a timer. A synchronization manager shall configure the hardware and ensure that the triggers are correctly managed for every experimental channel. All channels involved in the data acquisition shall be configured as well to participate in the data acquisition process (buffers, trigger inputs, etc.) and they ideally shall have a timestamp-source associated in order to handle timestamps to be saved with the data. Depending on the number of detectors involved and the data acquisition setup, a use of intermediate buffers that can temporarily store all or a significant part of the dataset may also be required. These buffers can be inside the detector or in an intermediate setup between the detector and the central data storage. High data rates detectors include these buffers to cope with slower systems. A generic solution for the management and maintenance of intermediate buffers must handle this complexity coming from the variety of detectors and requirements.

4.8.5 Continuous scan as the standard data acquisition system

First approaches to continuous scans are usually made "ad hoc" for a particular use case with a particular hardware. In order for them to be the standard data acquisition system they shall be generic, flexible and easy to configure. The natural approach would be to maintain the same interfaces or similar to traditional step scans. This is not trivial due to requirements of synchronization, hardware signals, configuration of the selected axis or combination of axes, acquisition speed, etc. Any combination of "movable" elements, such as motors and pseudomotors shall move synchronously in the given trajectory.

The arbitrary combination of detectors and monitors configured for that scan shall acquire synchronously reacting to the configured signals. These are of different types, such as scalars, one dimensional vectors for example "*Multi-Channel Analyzers*" (MCA) or "*Position Sensitive*

Detectors" (PSD)[155]; two dimensional imagers such as CCD[156] cameras or Pixel Array Detectors (PAD) or in general any number of dimensions.

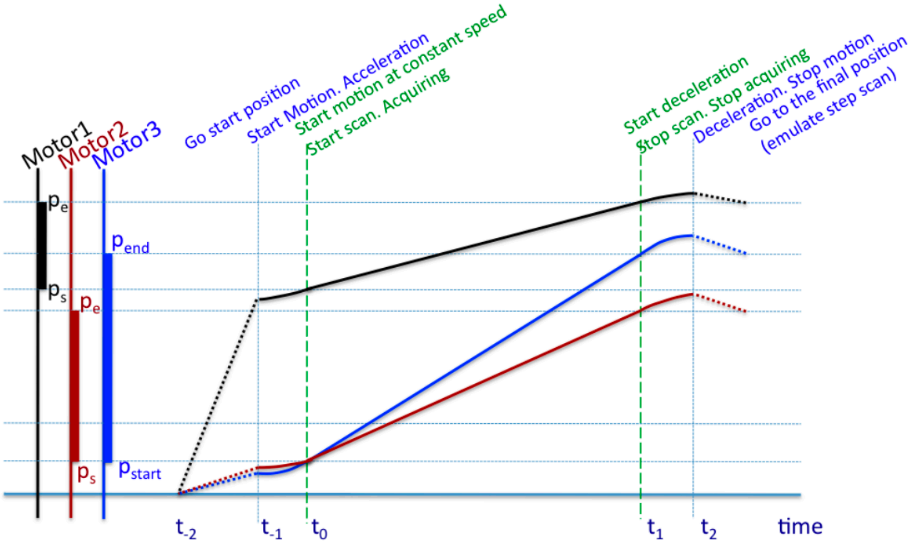


Figure 4-17: Position versus time in a continuous scan [4:23].

When considering linear motions, the motors shall start moving before the start of the scan, in order to allow beginning the acquisitions of the scan at the desired point at constant speed. In the case of the pseudomotors, setting both acceleration and speed in the final units is complicated, needing a cascade to the implicated motors. The Figure 4-17 describes the process where t_{-2} represents the initial state, t_{-1} is the initial position, foreseeing the space and time to accelerate. t_0 is the actual starting point of the scan, where all motors are synchronized and at constant speed whereas t_1 is the final point, where the last acquisition is done and the motors begin to decelerate. In order to keep compatibility with the step scan, the motors return to the end position and restore the preset velocity and acceleration.

A continuous scan usually needs a synchronization of different detectors combined with data interpolation from additional slow channels. The data acquisition takes place during the scan at synchronized intervals. The synchronization can happen at equidistant time intervals, naturally assuming a constant speed in all movable axes, or at arbitrary defined positions of the master axes.

[155] Position Sensitive Detectors (Chapter 5): Wikipedia: http://en.wikipedia.org/wiki/Position_sensitive_device
[156] Charged Coupled Device (Chapter 5): http://en.wikipedia.org/wiki/Charge-coupled_device

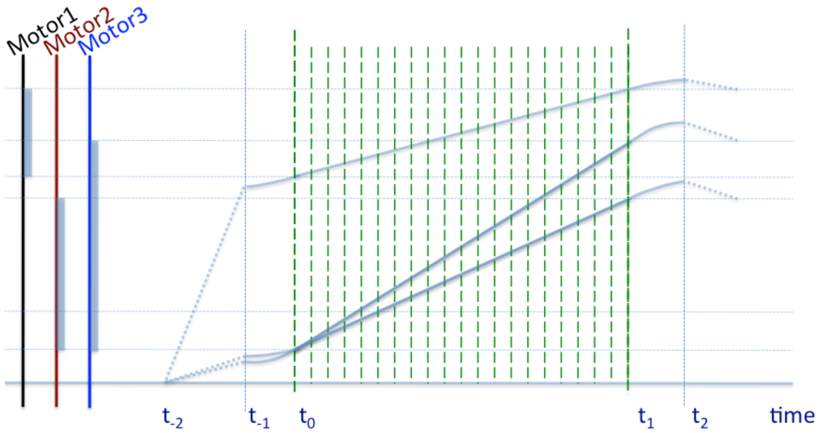


Figure 4-18: Representation of the synchronization signals assuming constant speed [4:23].

A trigger manager must configure the trigger signals computed from the source, either from a counter-timer device or from encoder or an indexer of an axis or set of axes. Normally, complex setups require dedicated instrumentation to manage the triggering schemas and to produce the signals according to the detectors needs. The detectors involved in this particular data acquisition of a scan shall be configured accordingly. Typically, a trigger can be a pulse or a gate (latched signal where the length corresponds to the exposure time). The pulse indicates the start of the acquisition and the detector manages the acquisition time that has been preset. The gate indicates the start and duration of the acquisition time. Slow process variables, such as temperatures, diagnostics etc., not triggered, could cohabit with the synchronized detectors[4:24][4:25].

This generic setup needs triggering and intelligent buffering capabilities. The buffer handles fast detectors with or without internal memory, slow channels, interpolation of data taken asynchronously or at slower rate, and rolling-buffers for large scans. Figure 4-18 and Figure 4-19 show the generation of triggers and the distribution of live and dead times (acquisition times and dead times). Slower signals and those that do not have trigger capability, such as temperature readouts or other measurements of the sample conditions, can also be integrated in a continuous scan. They need to be read at a slower pace and later integrated with the final data, following different configurable interpolation schemes.

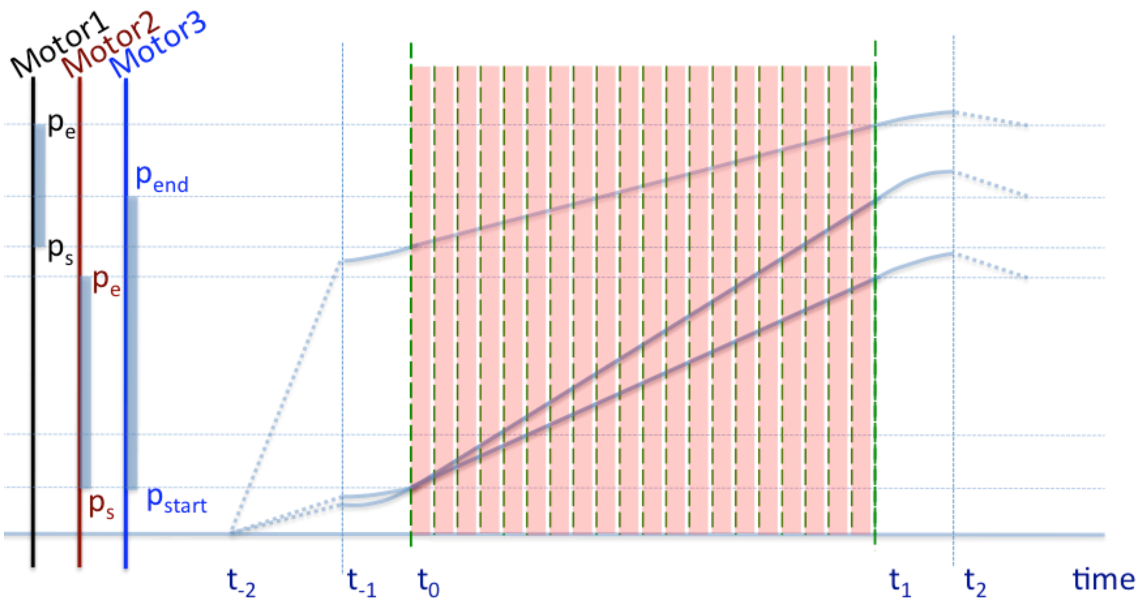


Figure 4-19: Representation of the exposure times and intervals of a continuous scan [4:23]

4.8.6 The benefits of a global timestamp in the data acquisition process at experimental stations and particle accelerators.

The key of synchronization is to precisely link a time with a measurement. External signal triggered acquisitions are assumed to happen the same time (*jitter*[157] is often in the pico-second range, whereas the exposure times are usually in the millisecond range or eventually microsecond, but always orders of magnitude larger). In this scenario, the lack of a global timestamp is mitigated since the absolute time is not known, but all signals are acquired at the same time and at the right time (trigger).

Providing means to associate a precise absolute time to every measurement reduces significantly the need of external synchronization. Theoretically, data acquisitions could be made at the fastest speed supported by the detector, and the data post-processing extract the measurements from the different channels and present them at grouped and normalized with the right exposure time. This approach can be explained as follows: it is important to use the detectors at the maximum of their capabilities. If they are configured to maximize the acquisition ("live time") and minimize the dead time (overheads)[158], the process would be more efficient. If the buffer size and management can follow this approach with the different

[157] Jitter: fluctuation in the generation or transmission of the signal, perceived as an imprecision in the reception or the trigger.

[158] Dead time is a concept related to the intrinsic physics of the detector (see chapter 5) and its capability to acquire photons. In this context "dead time" refers only to the overhead of the process (software, etc.) when the detector is not actually taking data.

detectors, the data could be post processed to prepare for data analysis, rearranging the data accordingly with the exposure times and synchronization. This approach presents the inconvenient of the time and computing power needed for this post-processing, and the need for the interpolation of data with the subsequent risks of artifacts. In any case, it is important for data visualization and analysis to manage the measurements grouped and presented in intervals and discrete points.

Depending on the desired precision and on the particular setup, timestamps may be synchronized by hardware or by software. Software synchronized times can have enough precision for a large number of setups. Network Time Protocol (NTP) and Precision Time Protocol (PTP) can reach one digit microsecond precision or better, although most old implementations of NTP are often below the millisecond range. The Table 5 shows the jitter and offsets measured on the NTP implementation at the ALBA synchrotron.

```
xxxsa01:/etc # date;ntpq -p;
Fri Aug 30 17:35:31 CEST 2013
remote                          refid  poll reach  delay   offset jitter
 =======================================================================
*xxxtimgpssr00      .PPS.       1 u   40   64  377    0.214    9.706 1.314
+xxxdms01                       2 u   27   64  377    0.371    8.936 1.657
+xxxcells                       2 u   53   64  377    0.385    5.262 1.811
```

Table 5. Offset and jitter measured on an NTP implementation at ALBA.

NTP timestamps are 64bits integers. Actually, they can be seen as 2 32bits integers representing seconds from January 1st 1900 at 00:00h (first 32bit integer), and fractions of a second up to $1/2^{32}$ second precision, that is 238 picoseconds (represented in second 32bits integer). This is sufficient for most experiments. This format reaches until the year 2036.

Although the technology offers many possibilities, this is not used for synchronization of the particle accelerators and Beamlines, which in terms of reliability and complexity of the system as aforementioned in this chapter (4.2.1) often needs dedicated hardware[159].

The accuracy required by the synchronization experimental setups depends on the particular station and experiment, but typically a single digit microsecond is in most cases sufficient.
For example, X-ray absorption beamline (ALBA-BL22) is equipped with a direct drive double crystal monochromator capable of moving at four degrees per second. Considering a silicon

[159]Taking again ALBA as the example, but the technology and the implementation is the state of the art nowadays, the synchronization of the particle Accelerators and Beamlines has been implemented using MRF hardware that includes a timestamp with 8 ns resolution and 25ps jitter RMS [4:6]. ESRF-EBS 2020, the new upgrade of the ESRF accelerators uses White Rabbit as timing system.

111 Bragg crystal (equation 1), the energy would be calculated as stated in the equation 2 from the incidence angle θ.

$$n\lambda = 2d \sin \boldsymbol{\theta} \qquad (1)$$

$$E(eV) = \frac{hc}{\lambda} = \frac{12398.419\text{Å}\ eV}{2*3.1354161\text{Å} * \sin \boldsymbol{\theta}} \qquad (2)$$

The energy is not linear with the incidence angle θ, but for small energy intervals at certain energies, we can assume linearity. For example, if we scan 1000 eV in the range of 8 keV, the Bragg angle moves by about 2 degrees. If the speed is configured to 4 degrees per second, the scan completes in 0.5 s, taking 2000 points (one point per millidegree or every 0.5 eV, which is suitable for a ΔE≈0.76 of Silicon 111). Acquiring data from an Alba Em (electrometer)[4:26] digitalized with an ADC (ADLINK2005, four channels 16 bits simultaneous at 500 kHz), we could theoretically have at least 80% live time, which makes (250000/2000)*0.8 = 100 values per scan point. Averaging these values, the statistical noise could be reduced by a factor of ten[160] (√100).

When the trigger generator computes encoder positions, equidistant pulses make constant angle intervals. If the trigger generator computes time, the angle intervals may have a jitter, when the speed of the Bragg angle is not constant, but the final energies correspond to the right measurements because both encoder counters and detectors ADCs received trigger signals. Scans synchronized at equidistant time intervals are suitable only for linear trajectories at constant speeds. Extending accurate timestamps to every value acquired, overcomes this limitation allowing any trajectory and even makes triggers not mandatory in certain conditions. Triggers will be needed to synchronize actions but not to timestamp the measurements. The problem comes from the fact that sometimes is not possible to assign precise timestamps to acquire data. The scan participants are configured to start and stop at the specified positions as described in the previous paragraphs. If the timestamps associated with the scan values are precise enough, the data taken are valid although they can have different acquisition intervals due to fluctuations of deadtimes. Similarly, data can be presented in the right format to be analyzed, for example interpolated to equally distant intervals, showing the same number of columns for all channels in order to make arithmetic operations.

The precision required in terms of jitter depends of the speed of the scan. In the previous example, the experiment requires to distinguish different consecutive energies. Considering 4 kS/s acquisition speed (therefore sampling every 0.25ms) the maximum jitter would be 125 ps peak to peak (0.25 ms/2) which determines the minimum accuracy of the timestamping system

[160](√n) This is not true when the noise is not white, for example when produced by mechanical vibrations, electromagnetic noise, etc.

for this experiment. In BER[161] values, assuming 99.999999% transmission accuracy (1 error per million points) the RMS jitter would be 125/9.507μs = 13.14μs. This result would fit into the 10 microseconds range requirement[162].

4.9 Ad-hoc developments. The Fast Orbit Feedback of a particle accelerator

Particle Accelerators and Experimental Stations produce requirements that require transversal solutions and projects involving a certain number of subsystems. One critical, present in most recent particle accelerators, that relies on well-known common principles and algorithms but that at the same time requires an ad hoc implementation based on the particular hardware of the installation is the Fast Orbit Feedback (FOFB). It typically requires correcting instabilities in the bandwidth range of about 100 Hz. Grosso modo it requires fast readouts from the beam position monitors and fast setpoints to the corrector's magnets power supplies: the requirements are shared by all particle accelerators, the correction algorithms are similar, but the implementation is specific depending on the beam position monitor electronics and the power supplies.

Once the particle accelerator is operational, the electron beam shall ensure a stability in the range of about ten per cent of its size: for example, in the case of ALBA, this translate into about a micron in the horizontal plane and 0.1 microns in the vertical plane. The slow orbit correction traditionally used in particle accelerators corrects static perturbations, thermal drifts, ground displacements etc. Local orbit feedbacks correct perturbations produced by elements like insertion devices. These are all superseded by the fast orbit feedback, which in most cases require correction forces up to 1 mrad, carried out by the corrector magnets.
Noise sources are multiple and diverse. Mechanical devices, human activities, railway and road traffic, ground and cooling circuit vibrations, insertion devices, Top-Up injections etc. produce noise in the short time scales. Thermal or other drifts on the vacuum chambers, movements of the ground are on a longer scale.

Top-Up operation consists of injecting charge to certain bunches in order to recover the overall current in the Storage Ring. This requires periodic injections every few seconds or minutes, which will inevitably provoke instabilities in the electron beam. These instabilities are typically of very high frequencies that are out of the reach of the fast orbit feedback but shall be optimized by other means (mostly related to fine tuning of the injection process).
The precise moment when top-up injections occur is known[163]- and therefore could be attenuated by other means, contrary to most cases where the perturbation appears unforeseen.

---

[161] BER: Bit Error Rate. Number of bit errors per transmitted unit. https://en.wikipedia.org/wiki/Bit_error_rate
[162] For a BER 1E-6, the corresponding scaling factor corresponds to 9.507. Jitter (Peak-to-Peak) = RMS Multiplier x Jitter(RMS). RMS multiplier (α) is calculated as follows: 0.5*erfc(α / $2\sqrt{2}$)=BER. For a BER=10^{-6} => α=9.507.
[163] Every 20 minutes and repeated every 3 Hz in the case of the ALBA Storage Ring as configured in 2014.

Other high frequencies perturbations provoked by RF *trips*[164] *kickers* pulses are for obvious reasons out of the reach of this regulation.

Insertion devices are operated by the Beamlines to carry out their experiments. In particular, in spectroscopy the insertion devices are scanned together with the monochromator to change the energy during data collection at the experimental station, which means continuous movements most of the time. These movements generate perturbations of a few microns (depending on the ID) in the range of 5 to 30 Hz. The 50 Hz perturbation is of course always present in all measurements, given by the frequency of the mains (in Europe). This is attenuated but very difficult to remove. The orbit correction ensures a stability better than 10% of the size of the beam below 100 Hz, however the 50 Hz and the harmonics (100, 150, 200 Hz, etc.) will always be visible.

4.9.1 Configuration of the system

In the orbit correction, the key players are the electron Beam Position Monitors (eBPMs) and their control electronics (inputs) together with the corrector magnets and their power supplies (outputs). It is a regular multiple-input multiple-output system. The Fast Orbit Feedback (FOFB) aims to correct perturbations at low frequencies, typically bellow 100 Hz. This implicitly assumes that the data acquisition rates at the Beamlines are bellow that limit which is no longer the case in certain Beamlines. The position of the beam (orbit) is measured by the eBPMs, compared with the reference and computed by using Singular Value Decomposition algorithms (SVD)[4:27][4:28][4:29] to produce a response vector to be sent to the power supply controllers. The response can be combined with PI controllers (Proportional, Integration, non-derivative). In the particular case of the ALBA Synchrotron, the power supplies were manufactured by OCEM and the control units are based on the electronics developed at PSI with digital regulation and communications based on Manchester encoded messages over direct fiber optics links [4:30]. This is an exception to the network communication standard and it is justified by the high bandwidth needed by the system not reachable by Ethernet links (the latency is even more critical than the overall bandwidth). Again, in the case of ALBA the eBPM readout electronics installed at the time were the Libera Brilliance[165], with 4 analogue channels sampling at 125 kHz and 12 bits. These modules fix the data acquisition rate at 10 kHz, which means completing the readout, calculations and writing set-points in less than 100 µs. ALBA Storage Ring can count from 104 to 120 eBPMs for the orbit correction, although a typical value is 88 (the number of corrector magnets in each of the planes)[4:32].

---

[164] A trip is a failure that provokes the shutting off of a RF plant, that can provoke other failures and the complete trip of the beam

[165] Libera is a product built and commercialized by I-tech, Slovenia. BPM. http://www.i-tech.si. These Libera electronics were later upgraded to later versions.

Institute	Bandwidth	stability
APS. U.S.	50 Hz	<1 µm
ESRF. France	100 Hz	<0.6 µm
SLS. Switzerland	100 Hz	<0.3 µm
DIAMOND. U.K.	150 Hz	0.2 µm
SOLEIL. France	150 Hz	0.2 µm
SPring-8. Japan	100 Hz	<1 µm
ELETTRA. Italy	80 Hz	0.2 µm

Table 6 : Comparison with a few Synchrotrons around the world (source: their public web pages)

The Libera boxes are interconnected between networks (copper within the cabinet and fibers between different racks in different sectors). There is a *sniffer*[166] installed in one cPCI that implements the transmission protocol of the Libera Modules, reads position monitor vectors. That cPCI has a quad-core CPU that implements the corresponding matrix calculations to produce the output vectors for the correctors. The computation is then parallelized between different cPCI computers. This is very innovative in the sense that the computers carrying out the calculations are neither dedicated CPUs (such as purpose specific CPU in an OS9-VME crate) not real time operating systems. The standard single-core CPU installed in the cPCI crates did not have the power to accomplish the task (Intel(R) Pentium(R) M processor 1.80GHz), and therefore a quad-core CPU was used instead (Intel(R) Core(TM) i7-2715QE CPU @ 2.10GHz). The kernel was compiled in preemptive mode (Linux SMP 2.6.27 CONFIG_SMP CONFIG_PREEMPT), which improves the response to interrupts and the overall performance of the whole system. The excessive latencies disappeared and the determinism improved significantly making the system stable[4:31]. Other fine adjustments at the OS level may be required, such as the scheduler, giving maximum priority and assigning a CPU core to the calculation process, moving other processes and IRQs[167] to other cores.

After extensive tests, the only drawback was that the overall cycle was slightly longer than the 100 µs given by the 10 kHz rate imposed by the Libera boxes (some of the tests took up to 120 ms). Therefore, it was necessary to downgrade the rate to 5 kHz, hence taking 200 µs for completing the cycle. The Figure 4-20 shows the block diagram of the FOFB hardware The

[166] The Sniffer is a PMC card by Micro Research Finland (http://www.mrf.fi/index.php/pmc-products), originally designed for the *Timing System*. The firmware (FPGA program installed in EPROM PCI9030) has been modified to read values from the Libera network: Credits M. Abbot, I. Uzun, G. Rehm at Diamond Light Source.
[167] IRQ: Interrupt Request. Hardware signal addressed to the CPU to temporally interrupt a process.

characterization, tuning and functional tests of the system have been carried out mostly by Jairo Moldes[168].

The fact that the correction is carried out in a regular cPCI crate running standard Linux makes easier both maintenance and the fine-tuning of the system. Other solutions would imply building hardware "ad hoc", dedicating a reduced subset of correctors for this task. In order to keep the performance and the flexibility, the next generation of the system shall follow the same approach or profit from the remarkable progress of the FPGA technologies (*Field Programmable Gate Array*), powerful enough to implement a system including a new communication protocol with the Power Supply electronics and the matrix calculations of the orbit correction algorithms (everything built on the FPGAs).

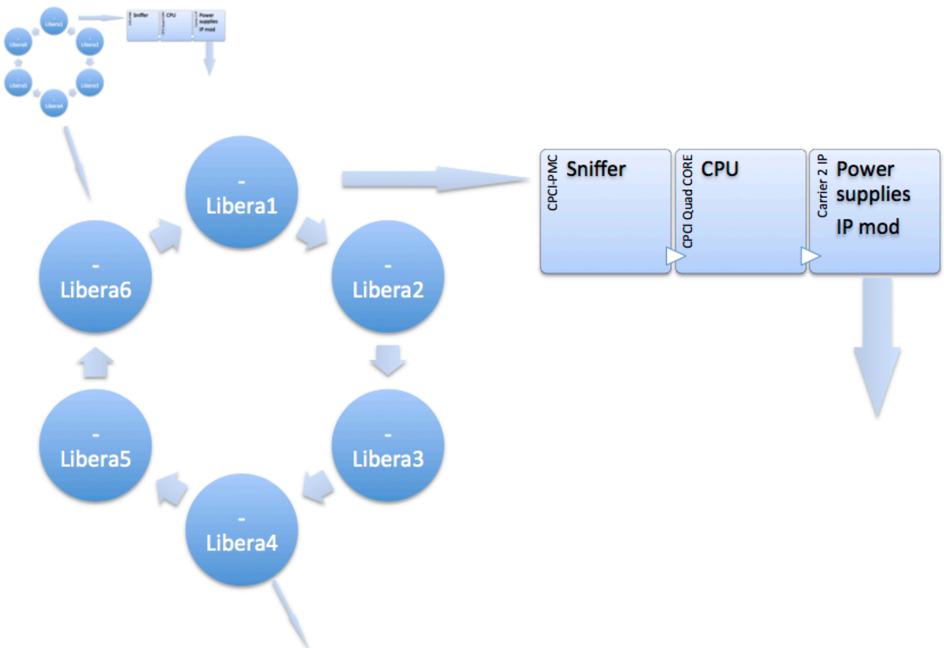


Figure 4-20: Schematic of the Libera network and the cPCI crates devoted to the correction. The 6 Liberas per sector can be incremented according to the particular architecture.

4.9.2 Data acquisition and processing

The possibility of splitting the calculation of the algorithms amongst 16 sectors is key for this solution to work. The "*communication controller*", implemented in the FPGA of the Libera modules and the sniffers, works similarly to a reflective memory bringing the orbit

---

[168] The author would like to thank Jairo Moldes from ALBA controls section who refactored and wrote most of the code and is actually currently maintaining the software and Alejandro Homs from the ESRF, who played a decisive role in the commissioning of the kernel and the quad-core setup for accomplishing this task.

measurements (horizontal and vertical beam position values) to each of the 16 cPCI participating in the correction[4:28][4:32].
The Singular Value Decomposition (SVD)[169] can be seen as a method to transform correlated variables into other uncorrelated and to analyze the variation in different planes reducing the number of dimensions. The algebra says that any rectangular matrix can be decomposed in the product of three. One orthogonal U, one diagonal Σ and the transpose of the orthogonal V:

$$A_{MN} = U_{MN}\, \Sigma_{NN}\, V_{NN}{}^{T}$$

Where $UU^T = I$ and $V^TV = I$, the U columns are eigenvectors AA^T, the V columns are eigenvectors of A^TA and Σ is the diagonal matrix with the roots of U or V in descending order. This decomposition makes filtering and processing simpler, by acting on the eigenvectors or for example inverting the matrix. Considering that there are M eBPM and N correctors (88x88 is the case of the ALBA Storage Ring), the correction can be seen as:

$$R\theta = \Delta$$

with $R_{MN} = U_{MN}\Sigma_{NN}V^T{}_{NN}$

(R is the response matrix, Σ (sigma) is the diagonal matrix composed of eigenvalues, θ (theta) is the vector of angles introduced by the correctors and Δ (delta) are the measured displacement vectors with respect to the reference orbit.

Since θ is the result of the correction, hence:

$$\theta_N = R^{-1}{}_{NM}\Delta_M$$

with $R^{-1} = V\Sigma^{-1}U^T$

The Figure 4-21 shows a representation of the inverted response matrix for the horizontal plane (there is an equivalent for the vertical plane as well), where the values out of the diagonal have clearly a smaller contribution.

[169] SVD: https://en.wikipedia.org/wiki/Singular_value_decomposition

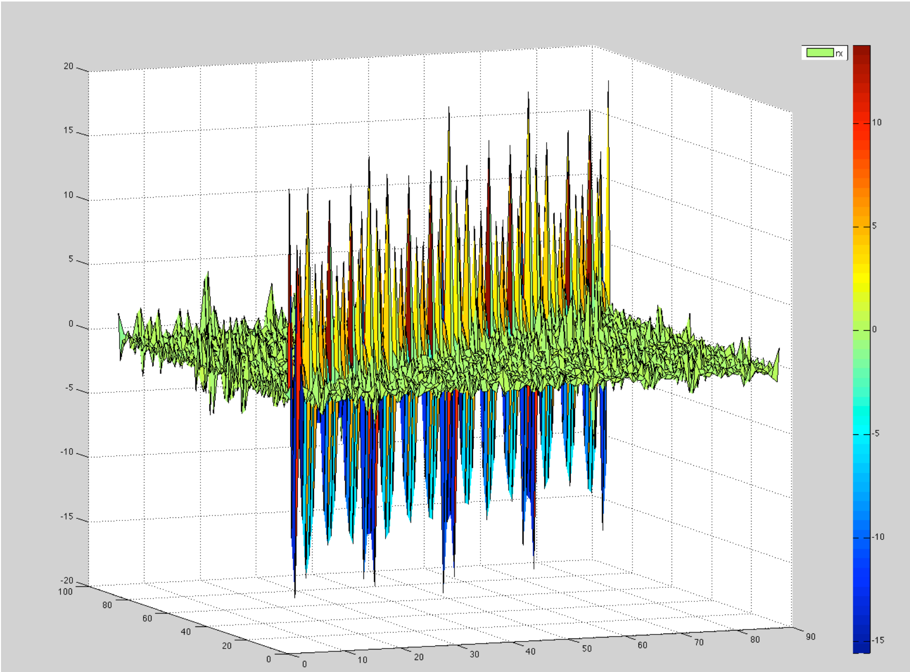


Figure 4-21: 3D representation of the inverted response matrix in the horizontal plane.

Eventually extra correctors may be needed in the final implementation, such as for example readouts from the X-ray Beam Position Monitors (xBPM[170]) in the Front-Ends give a good compliment to the eBPM network at the cost of adding extra dimensions to the matrixes.

The multiplication of matrixes is the critical operation during the feedback, since the response matrix is already inverted. The mathematical operation at every cycle is the following:

$$\theta_X = R^{-1}{}_{XM}\Delta_M$$

where X is the number of correctors per plane in the sector[171].
In addition, the multiplication can be accelerated with specific instructions of the type `_mm_mul_ps` parallelizing four simultaneous floating-point operations and reducing the overall number of operations per CPU (that must only perform the operations corresponding to that sector), making the latency goals achievable.

[170] X-ray Beam Position Monitors: Monitors conceived for X-rays. They usually have as well four readouts, although occasionally they could give only two.
[171] In the case of the ALBA Storage Ring, this varies between 6 and 7 in each plane.

4.9.3 Data filtering

It is possible to tune or zero some of the coefficients of some eigenvectors to match imperfections, latencies, etc. Besides, the correction algorithm can include a regulator PI (Proportional-Integrative) that is often tuned experimentally [4:31][4:32].

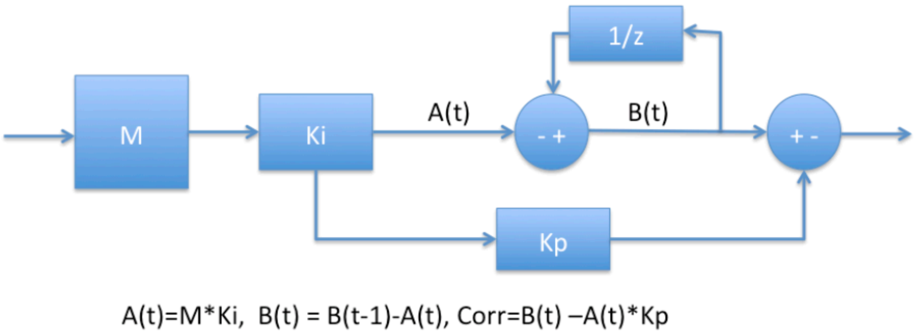


Figure 4-22: Introduction of a PI regulator to the correction process.

The whole system has an intrinsic overall latency measured since the perturbation occurs until the correction is applied. The latency can reach 2 ms. This is the total time taking into account the bandwidth of the eBPMs, the data transmission time across the eBPM network, the sniffer readout time, the calculation time, the power supplies, transmission and delays, and the bandwidth of magnets and vacuum chambers. Figure 4-23 shows the orbit distortion provoked by a corrector magnet for test purposes and the time the eBPM takes to notice it (green curve). It is measured in pulses 200 µs long (given by the 5-kHz sampling rate of the orbit correction). The blue curve represents the setpoint in the corrector magnet power supply, that needs to be converted in an electric and magnetic field applied by the magnet to the vacuum chamber. The overall delay counting the aforementioned reaches 2.5 ms.

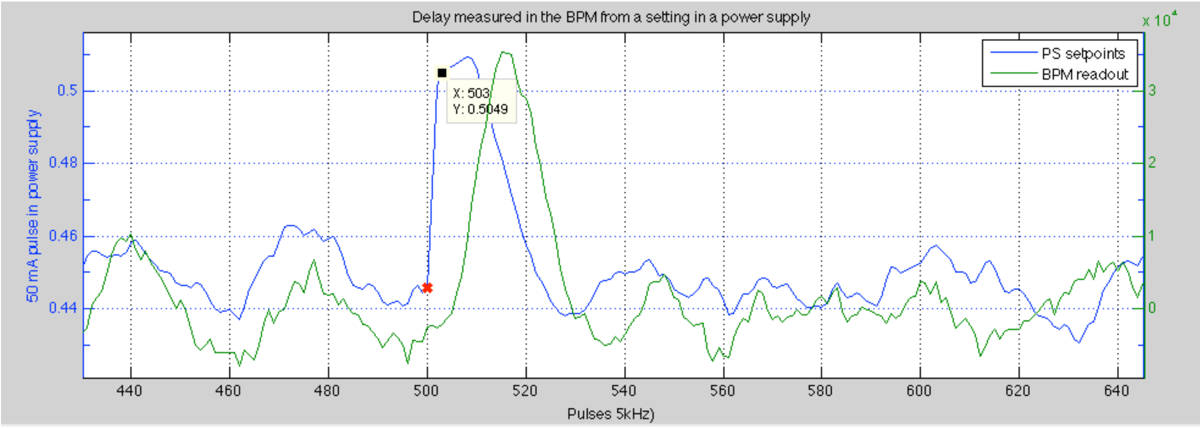


Figure 4-23: Delay observed since a perturbation provoked by a corrector (50 mA current change) until it is registered by the eBMP (this is in the order of 2.5 ms, 13 pulses of 200 µs).

4.9.4 Fast Orbit Feedback and Top Up, from the experimental station point of view

Topping up (periodic frequent re-injections) produces perturbations with high frequencies impossible to correct with the FOFB. The perturbations introduced by the Injection Kickers are in the order of a few microseconds and the FOFB works on a 100 Hz bandwidth. These perturbations are seen as intensity drops at the experimental stations, that could be eventually corrected or mitigated by means of specific normalization with monitor counts. The Figure 4-24 shows the effect of the kicker magnets in the experimental stations. The measurements were taken at ALBA-BL29 with the fast orbit correction enabled and disabled.

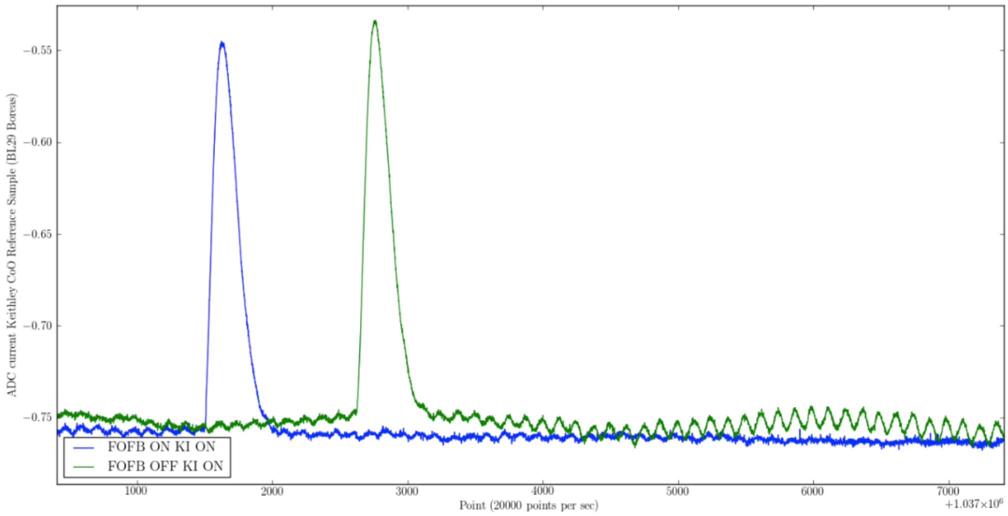


Figure 4-24: Distortion provoked by the injection kickers with the FOFB enabled (blue) and disabled (green), measured at the experimental station of a beamline (ALBA-BL29).

These measurements show a repetitive pattern with a period and a frequency slightly attenuated when the FOFB is enabled. Repetitive measurements did not conclude that the oscillations come directly from the electron beam and that the FOFB has a clear impact on these oscillations. It is clear however that the injection kicker magnets provoke a substantial noise that degrades the data quality. Further adjustments such as improving the shape of the *bump*[172] created by all kickers intervening in the injection are critical success factors with demonstrated impact in the data quality.

4.10 Name convention, documentation and the installation database repository

A synchrotron as other large installations is built foreseen an operation of at least 30 years. In order to optimize the maintenance and change processes along these years is important to define upfront consistent naming conventions for both hardware and software. TANGO device names are made of 3 parts "*Domain/Subsystem/Member"*. Each device declared in a device server (process) implements Attributes and Commands.

The naming conventions define and agree on names of components, instruments, cabinets, cables, connectors, etc. and in terms of usability they shall be as intuitive as possible. Following the convention (System/Subsystem/Name-sequence), the name SR.CT.RKA10B03 can represent a cabinet located in the sector 10, 3rd at the row B, part of the control system (CT) of the Storage Ring (SR). These conventions encompass also labeling, documentation and proper documentation of different processes, such as cabling for example, that can be outsourced to different companies requiring a quite complex organization of the project.

4.10.1 The central hardware repository database

As aforementioned, the installation of a machine of these characteristics require different contracts with suppliers working simultaneously on-site, with in many occasions a strong interdependence amongst them. The central and up-to-date repositories are critical success factors for the coordination of the works, improving the accuracy and details of the documentation, reducing the number of errors and the installation time. The documentation shall be as detailed and accurate as possible, and this is even more critical when there are external companies involved, counting potentially with newcomers to whom the explanations must be detailed (assuming they do not have previous knowledge) and precise (they are not as well trained as experts to detect mistakes).

[172] Bump: The distortion applied by the injection kickers to the electron beam orbit. Typically, the common four-kickers configuration creates a step separating the beam from the nominal orbit to then bring it back to the original trajectory. The accuracy to bring back this step to the original trajectory is known as "closing the bump".

A central repository [4:33] is the key tool to configure, register and document instruments, connectors, cables, equipment types, racks, etc. which are first defined and then instantiated with a final position in the installation. This enforces keeping the documentation centralized and up-to-date and allowing a certain traceability of the instruments and pieces of equipment. The management of stocks is another key aspect for the whole installation. During operation, the maintenance process requires the use of spare parts, which shall be managed in terms of availability and traceability, to keep maintenance records and statistics of failures.

A database containing all instruments, with channels, connections and cables is an inestimable starting point for the software to produce automatic declaration of variables and after all even process logic, resulting in a better quality with less errors.
In particular, this is interesting for the PLC subsystems with a large number of variables and hardware connections, interconnected with the middle layers and the SCADAS. Other services such as the network DHCP, DNS or RADIUS authentication can certainly also profit from this repository to automatically get Ethernet-MAC addresses and maintain the databases up-to-date synchronized with this central repository.

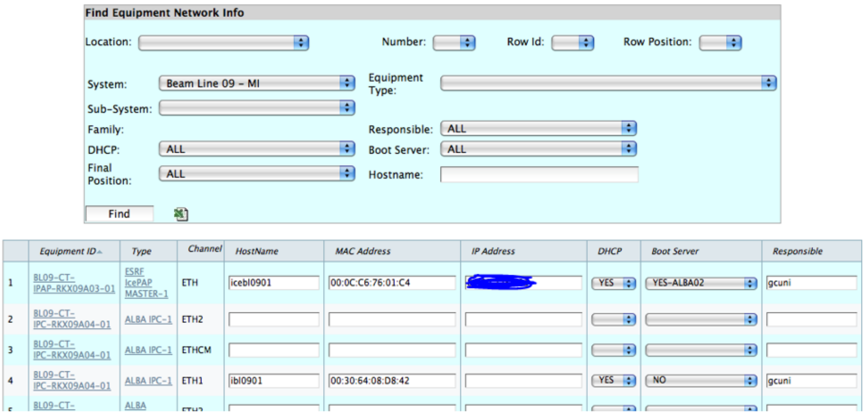


Figure 4-25: View of the web interface to the cabling database at ALBA (corporate hardware repository)[4:33]

In summary, the centralization of the information from early stages brings the software development coupled to the hardware installation. When a new piece of equipment is renamed or modified, for example a temperature sensor connected to a PLC, the whole documentation can be regenerated and distributed to the external teams, software developers, network administrators, etc. The whole chain from the declaration of variables in the PLC, the attribute and variable names in the middle layer (for example TANGO), and after all the graphical panels in the SCADA would be automatically updated [4:34].

4.10.1.1 Connections, stocks and maintenance interventions

As discussed in the previous paragraph, this central repository is at the core of the installation and contains implementation details to be used in the technical specifications of the call for tenders, the execution of the contracts and the installation and maintenance processes. The installation tasks of the instrumentation, the cables and the control system are often scheduled towards the end of the project. This is motivated by the civil works needed to be well advanced before starting with other tasks in these areas. The installation of racks[173], instruments and internal cables requires time and effort and therefore it is a candidate to parallelize with the civil works. A preinstallation of racks with instruments and cables requires a dedicated area and the central documentation to be consistent and not subjected to many changes. A preinstallation of racks, includes all the instruments inside the rack, labels, cables and connectors. Once the racks are in the final position (ideally this shall be carried out during the preinstallation), all channels of every instrument and piece of equipment in the rack, shall be documented and labeled accordingly in order to define the cabling processes to be handled to the outsourced companies.

Having these details documented in a central repository allow to pre-install racks (Figure 4-26) and pre-configure them with the appropriate software. The pre-installation of equipments speeds up the coordination of tasks and the final installation. These racks would probably not be able to be installed until much later in time when the civil works are finished and the area is clean up and properly conditioned.

Figure 4-26: Left: Preinstallation area at the ALBA warehouse. Right: Cabinet preinstalled with network equipment.

As abovementioned the central repository database needs to define types of equipment, cables and connectors and then instantiate them with entries. The definition of the equipment types is

[173] Racks: Cabinets usually with 19 inches rails to install instruments and pieces of equipment.

a very time-consuming task needing patience. It is tempting and much faster to keep these records in excel files, which inevitably would become inconsistent (types duplicated, redefined or incomplete) and outdated. Another key aspect is the follow up of tasks and the traceability, keeping records of the interventions of corrective maintenance, serial numbers involved, and eventually a calendar with the preventive maintenance work orders.

4.10.2 Naming convention equivalences between hardware and software

TANGO (software) names (domain/subsystem/member) map the structure of the installation from an engineering point of view. For example, a power supply is referred as such and not as the magnet where it is connected. Therefore, the control system shall foresee aliases. The central repository database (hardware) follows the naming convention of the institute. Sometimes the software and hardware conventions are slightly different but they must keep a direct relation (Table 7).

TANGO Convention	*Corporate central repository*
Domain	*System*
Subsystem	*Subsystem*
Member	*Family*

Table 7: Correspondence between the name convention of TANGO and the naming convention at ALBA implemented in the central corporate repository database (cabling database).

4.10.3 Learning from experience in a continuous service improvement

This corporate central repository database (known at ALBA as the cabling database) is a clear competitive advantage with respect to other installations. In fact, and despite of the complexity of adapting the naming convention, it has been packaged and exported to other installations (MAXIV, ELI-ALPS[174] amongst others). The software has been developed and maintained by the Management Information System section at ALBA and has always been intended to be shared, but the great difficulty comes from an initial design strongly coupled to the ALBA naming convention and the particularities of naming conventions in all institutes. Besides, the technology (Plone2) for the human machine interfaces is not easy to maintain and export.

Another critical issue is the lack of support for equipment inventories and spare parts stock management. The initial database was conceived as a snapshot of the installation, with all pieces of equipment and instruments installed in their position and named accordingly. Each code represents a piece of equipment in the installation, with no information of the spares for

[174] ELI: Extreme Light Infrastructure. It has three pillars in Czech Republic, Romania and Hungary (ELI-ALPS) financed with European funds.

that equipment, their quantity, location, serial numbers or the number of times that has been replaced. This feature is a great added value to be included in further projects. The traces in the logbooks will be more complete, the identification of recurrent problems will be easier and the management of spare parts stocks will be simpler. In other words, maintenance will be easier (See chapter 6).

4.11 Control system administration. The evolution of management tools

The control systems rely on a large set of computers, front-end IOCs, cPCIs, industrial PCs, servers and an increasing number of virtual machines. They all have complex configurations and setups that require a specific system administration. The control systems configure purpose specific drivers, services and processes managed at the booting time. The computers of a control system integrate generic system administration tasks such as services started while booting, cron-tabs backups etc. They also manage services and processes directly related to the control system that can be either common to all computers of a kind or particular to that specific computer. In order to increase the overall reliability and make the sysadmin more convenient, a single operating system image is used for a group of computers often diskless booting remotely from a server. This is the strategy chosen at ALBA particle accelerator where most cPCI chassis (about 120) and industrial PCs (more than 30) get the operating system from a central "boot server".

However, as aforementioned, each of these computers have different PCI boards and need to load different drivers and different components of the control system with different configurations. A solution can be NFS[175] mounted specific directories for the control system admin. These directories contain a structure with all packages and configuration files, such as for example for Linux environments:

- Generic init files (`xxx.rc`)
    - That can be combined with particular init files (`XXX-$HOST.rc`)
- Generic startup files (`/etc/init.d/tango`, `/etc/init.d/archiving`, etc.)
- Individual repositories, such as for example the Python *Device Servers* may have dependencies installed in "`$XXX/lib/python2.7/site-packages`" instead of "`/usr/lib/python2.7/site-packages`" and therefore they do not interfere with the host operating system.

[175] NFS: Network File System.

4.11.1 Configuration management, software packaging and continuous integration

It is convenient to have a software package repository for accomplishing the deployment. The possibility of installing and rolling back packages is a must in these scientific environments. The rollback can be for different reasons: a bug, incompatibilities with some particular hardware present at a particular Beamline, or in general any software or hardware not working properly with the newly installed package. The size of the control systems and their large number of computers forces to properly manage releases, versions, installation logs and dependencies, and ultimately automate the whole process. There are many solutions with advantages and inconvenient. Nowadays a certain continuous integration and deployment is present in most systems. ALBA adopted from the beginning a model based on RPM[176] packages based on the Blissbuilder/Blissinstaller developed at the ESRF (L. Claustre et al.). It manages rpm packages with a mysql database handling versions and installation logs in the different computers. The Figure 4-27 shows the graphical user interface to install packages (Blissinstaller). There is also another graphical interface to build the packages (Blissbuilder).

Keeping the control system packages separated from the operating system standard packages brings a number of advantages, such as installing different versions of the same package for different applications (and different as well from the standard installed by the operating system). The operating system platform tries to be homogenized, sharing the same image installed in large number of computers and kept for several years.

These tools have showed a great potential at both the ESRF and ALBA. They keep a detailed register of the versions of each package in every computer and are fast and straightforward.

[176] RPM: RedHat Package Manager. Nowadays extended to other Linux distributions such as SUSE.

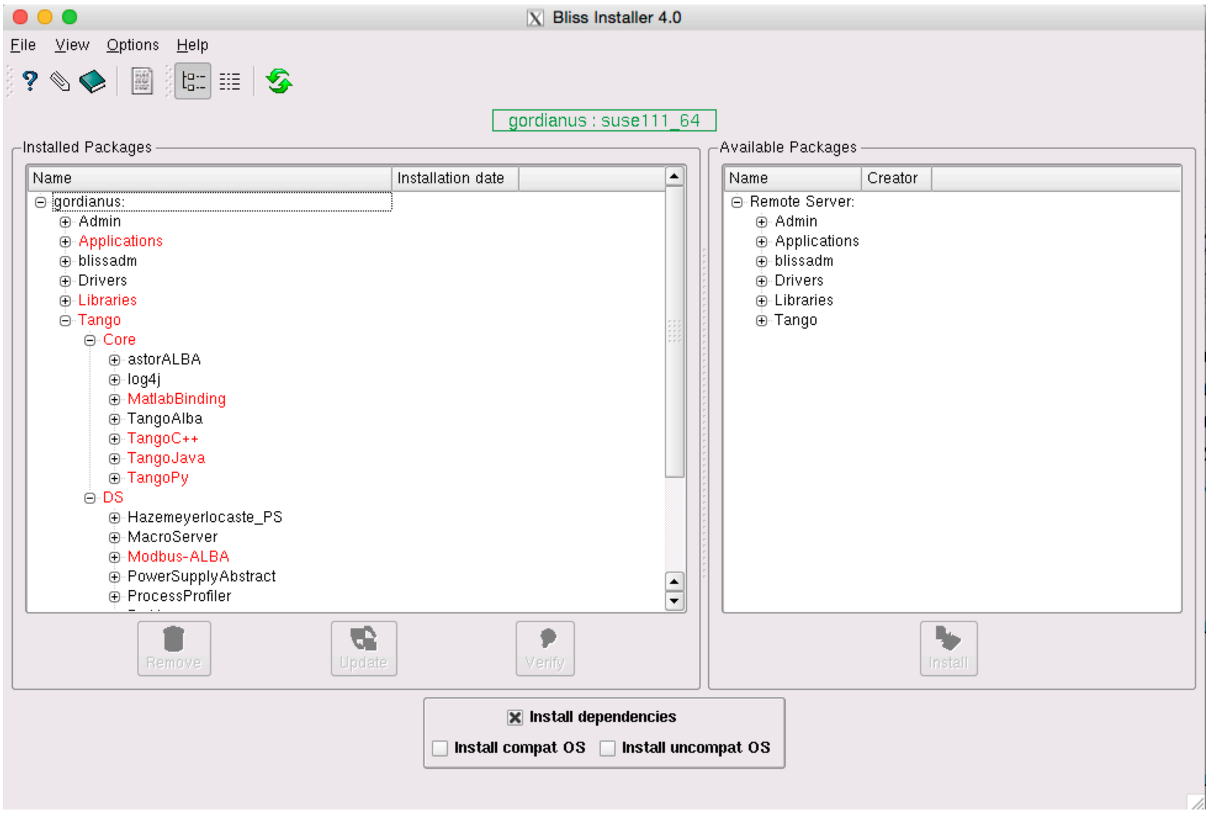


Figure 4-27: View of the graphical interface of the Blissinstaller (L.Claustre et Al. ESRF.

The biggest inconvenient is the difficulty of sharing packages across different institutions, using different operating systems and different hardware. Even if they had the same operating system platform they would very likely have different package structures for their control systems. One solution to share packages between institutes, besides working with the source repositories is to install packages in the default locations given by the platforms, such as (/usr/local for example) and distribute them as standard .deb (Debian) or .rpm (RedHat, OpenSuse, …) which would be published in the official repositories of the distribution.

Continuous integration tools like Jenkins[177] foster a greater integrity and quality of the software, making periodic compilations and tests [4:35]. Although Jenkins can carry out Blissinstaller tasks, a rational use would recommend using Jenkins in development and test platforms and the Blissinstaller “only” to install/uninstall packages in the final locations.

The market has evolved very fast in the last years and today DevOps concepts and tools are widespread. Development and operation teams are more than ever interconnected and tools for

[177] Jenkins: Free software for continuous integration. https://jenkins-ci.org/

configuration management and application deployment such as Ansible[178], SaltStack[179] (Python based) or Puppet[180] among others achieve a great level of automation. The continuous integration, continuous delivery and continuous deployment concepts require software version control, automated tests and the coordination of the software developers with the system administrators for the harmonization of the deployment process, including applications and operating systems.

4.11.2 Version control, source repositories and licenses

Large installation´s control systems are often Free and Open Source Software[181] with GPL or LGPL[182] licenses. Traditionally the source code repositories used to be locally managed with the consequent inconvenient to share, collaborate and also ensure the overall quality. Systems such SCCS[183] or RCS[184] appeared in the seventies and eighties to give answers to the developer needs, but the implantation was limited. Later in the XXI century, newer systems such CVS[185], SVN[186] or Git[187] took over and started to be extensively used. These systems were no longer used in local repositories but moved to public and more accessible to wide and growing collaborations, such as Sourceforge[188], Bazzar[189], GitLab[190] or Github[191] (complemented in some cases with copies of stable release packages in other repositories such as Pypi[192]). The version control systems and the public repositories make collaborations easier and enforce keeping the documentation updated and complete and the source code cleaner with more intuitive and institute independent structures. EPICS uses Bazaar, TANGO, Sardana, Taurus went through different systems across the years (CVS, SVN and later Git) in different repositories (Sourforge and later Github). The tools can change along the years, but international collaborations of different institutes force a version control system with clear rules for the contributors and public repositories.

178Ansible: https://en.wikipedia.org/wiki/Ansible_(software)
179SaltStack: https://en.wikipedia.org/wiki/Salt_(software)
180 Puppet: https://en.wikipedia.org/wiki/Puppet_(software)
181 Free and Open Source Software and Open Source are not exactly the same thing. There are many different flavors as stated in Wikipedia: https://en.wikipedia.org/wiki/Free_Software_Foundation
182 GPL: Gnu Public License. LGPL: Lesser Gnu Public License
183 SCCS. Source Code Control System. Software tool to track changes in the source code. https://en.wikipedia.org/wiki/Source_Code_Control_System
184 RCS: Revision Control System by GNU. https://en.wikipedia.org/wiki/Revision_Control_System
185 CVS. Concurrent Versions System. https://en.wikipedia.org/wiki/Concurrent_Versions_System
186 SVN. Subversion. Successor of CVS, software revision system. https://en.wikipedia.org/wiki/Apache_Subversion
187 Git. Distributed revision control system. https://en.wikipedia.org/wiki/Git
188 Sourceforge: http://sourceforge.net/
189 Bazaar: http://bazaar.canonical.com/en/
190 GitLab: https://about.gitlab.com/features/
191 Github: https://github.com/
192 Pypi: Software repository for Python. https://pypi.python.org/pypi

4.12 Summary

The design of control systems must be functional (fit to purpose) and cost-effective (fit to budget). Scientific installations integrate a large number of devices and instruments geographically distributed across hundreds of meters or even kilometers. Industrial fieldbuses are converging to Ethernet based networks in some cases adapted to offer deterministic behavior. In most cases these networks are standard TCP/IP based as the sizes and data volumes are getting larger and the determinism is only needed in few particular cases. Standard platforms used to be VME and later cPCI crates and industrial PCs[193] but this is already moving to newer chassis such as micro or Advanced TCA[194][4:36] with an extremely large bandwidth and new paradigms like the Internet of Things[195] very cost effective and flexible. Deterministic real time operating systems such as VxWorks or RTEMS often run on VME leave the place to standard Linux based kernels, simpler to maintain and configure keeping the standards of the installation. Sometimes, as aforementioned in the case of the ALBA Storage Ring orbit correction, they are compiled with preemptive options (CONFIG_PREEMPT) to allow low priority tasks to be interrupted even when executing system calls or interrupt handlers. Real time operating systems give specific answers to particular problems although they are no longer required in the deployed standard infrastructures. This is possible because the specific applications that require a deterministic behavior are managed by specific systems either commercially available or implemented "ad hoc" with specific tools (designs based on FPGAs, with transmission on Fiber Optics, etc.). Few examples are the Timing system, implemented with specific hardware and length-calibrated fiber optics, the Equipment Protection Systems, implemented with PLCs and deterministic networks (i.e. Ethernet PowerLink), or the Personnel Safety System implemented with certified Safety PLCs, sensors, actuators and Safety Buses. The Orbit correction could fall in this category, but given the specifications it could equally be accomplished by standard computers such as the solution implemented at the ALBA Storage Ring, where the standard correction algorithms, based on SVD matrix decomposition are performed in sixteen standard CPU running conventional Linux kernels. This is innovative in the sense that real time operating systems such as VxWorks or specific FPGA developments are no longer needed keeping the system according to standards and at the same time cheaper, easier to maintain and to implement changes. This distributed architecture allows to breakdown the matrix operations to be executed in sixteen different CPUs in parallel and reach 5 kHz sampling rates, proven fast enough to meet the requirements.

PLC systems, extensively used in industry are also getting more presence in scientific installations. The Equipment Protection Systems and the Personnel Protection Systems are two

---

[193] cPCI vs VME: Some institutes like CERN or the ESRF use VME extensively as the standard platform due to its robustness and longevity and despite of the fact that it is now surpassed in many ways by newer form factors.
[194] ATCA: Advanced TeleCommunications Architecture.
https://en.wikipedia.org/wiki/Advanced_Telecommunications_Computing_Architecture
[195] Internet of Things: https://en.wikipedia.org/wiki/Internet_of_things

examples of transversal systems profiting from this technology. PLCs have evolved in connectivity, interfaces and also very important nowadays, cybersecurity. The number of manufacturers is larger offering a large variety of input-output cards and connectivity. Traditional fieldbuses such as X2S in B&R PLCs or SafetyBus in Pilz safety PLCs are now combined with deterministic networks (for example Ethernet PowerLink for B&R and SafetyNET for Pilz). Obviously, the protection systems that manage risks to the personnel follow specific standards in the whole process of design, implementation, installation and validation, as described in the norm IEC 61508.

Control Systems tend to reduce the number of physical computers and exploit the Ethernet of Things paradigm using Ethernet as fieldbus and virtualization. The client-server models are a widespread solution for the geographically distributed instruments. These models are complemented with SCADA applications that combine the different tools with centralized and intuitive human machine interfaces. Indeed, SCADAs are now found in scientific installations, integrating PLCs and industrial control systems with the ad hoc scientific control systems.
TANGO and EPICS developed as free and open source software are good alternatives to build control systems in scientific installations. Most new facilities choose any of these options and discard developing a new system from scratch, which was common in the past. Nevertheless, both TANGO and EPICS do not give a full solution to many of the requirements of a typical experimental station. They are both a middle layer offering a communication channel with a set of tools to manage the infrastructure. Applications and tools like SPEC or Sardana complement EPICS and TANGO to tackle specific requirements of the Beamlines and experimental stations. SPEC supports different diffractometer geometries, a macro execution environment and a large support to different hardware. Sardana tackles the same problems, with a particular emphasis in the support of several simultaneous human machine interfaces: graphical and command line.

Continuous scans are at the heart of the state of the art control and data acquisition systems in light sources experimental stations. They are also extensible to neutron sources and other laboratories. Time resolved experiments need detectors capable of acquiring fast frame rates synchronized with a combination of motions and other monitors and detectors. This leads to time resolutions in the microsecond range and data acquisition speeds of several hundreds of Mbytes/s[196]. Besides, although when the experiment does not need temporal resolution, fast acquisitions are more beneficial in some conditions, by reducing the thermal drifts, and different sources of noise coming from the environmental conditions. In addition, the faster is the data acquisition the lower is the radiation damage of the sample.

[196] The data acquisition speed and the time resolution are the figures of merit that are continuously improved to perform new experiments. Today, there are detectors available offering already GB/s rates, a figure which will increase with time. The same with the time resolution, where microseconds are enough for most experiments but this will be reduced to nanoseconds and better, depending not only on the detectors but also on the motion and synchronization instrumentation.

Producing general purpose environments for continuous scans is considerably more complex than for step scans, given the fact that any motor or combination of motors and any detector or combination of detectors and monitors can potentially participate and need to be properly synchronized and adequately prepared for buffering, acquiring an eventually visualizing the data.

A corporate equipment database that handles instrumentation, cables, connectors and connections proves to be a strategic asset during the installation phase and during operation for maintenance purposes. Whenever it is up to date it will became the central access point for the documentation, the configuration of the instruments, and even the central logbook for interventions in these pieces of equipment. It can also be the source for automatic generated variable and hardware declarations in PLC systems, and even logic, programs and upper level control system software components.

4.13 References

[4:1] D. Fernández-Carreiras, D. Beltran, T. Coutinho, G. Cuní, J. Klora, O. Matilla, R. Montaño, C. Pascual-Izarra, S. Pusó, R. Ranz, A. Rubio, S. Rubio-Manrique, R. Suñé. "The design of the Alba Control System: A cost-effective distributed hardware and software architecture". Proceedings of ICALEPCS 2011 (p. 1318). Grenoble. France.

[4:2] D. Fernández-Carreiras, F. Becheri, S. Blanch, T. Coutinho, G. Cuní, J. Klora, C. Pascual-Izarra, S. Rubio-Manrique, R. Suñé. "Alba, a TANGO based control system in python". Proceedings of ICALEPCS 2009 (p. 709). Kobe, Japan. http://www.esrf.eu/computing/cs/tango/tango_doc/kernel_doc/ds_prog/tango.html

[4:3] D. Fernández-Carreiras, F. Becheri, S. Blanch, A. Camps, T. Coutinho, G. Cuní, J. Gigante, J. Klora, J. Lidón, O. Matilla, J. Metge, A. Milán, J. Moldes, R. Montaño, M. Niegowski, C. Pascual-Izarra, S. Pusó, J. Jamroz, Z. Reszela, A. Rubio, S. Rubio-Manrique, A. Ruz. "The commissioning of the control system of the accelerators and Beamlines at the Alba Synchrotron". Proceedings ICALEPCS 2011 (p. 432). Grenoble, France.

[4:4] D. Beltran, F. Becheri, D. Fernández-Carreiras, J.V. Gigante, J. Klora, L. Krause, M. Lipinsky, "PCI/cPCI Interface for the PSI power supply controller", Proceedings of ICALEPCS 2009, Kobe, Japan.

[4:5] A. Salom, F. Pérez, "Digital LLRF for Alba Storage Ring", Proceedings of EPAC08, Genoa, Italy.

[4:6] O. Matilla, D. Beltran [on leave], D. Fernández-Carreiras, J. Jamroz, J. Klora, J. Moldes, R. Suñé. “Alba Timing system. A known architecture with fast interlock system upgrade”. Proceedings ICALEPCS 2011 (p. 1024), Grenoble, France.

[4:7] J. Moldes et al. “The MRF timing System. The complete control software integration in TANGO”. Proceedings ICALEPCS 2011 (p. 484). Grenoble, France.

[4:8] B. Fernández-Adiego, E. Blanco-Viñuela, I. Prieto Barreiro, “UNICOS CPC6: automated code generation for process control applications”, Proceedings ICALEPCS 2011 (p. 871). Grenoble, France

[4:9] D. Fernández-Carreiras, D. Beltran, J. Klora, O. Matilla, R. Montaño, M. Niegowski, R. Ranz, A. Rubio, S. Rubio-Manrique. “Alba, The PLC based protection systems”. Proceedings of ICALECPS 2009 (p. 397). Kobe, Japan.

[4:10] D. Fernández-Carreiras, D. Beltran, J. Klora, J. Moldes, O. Matilla, R. Montaño, M. Niegowski, R. Ranz, A. Rubio, S. Rubio-Manrique. “Personnel Protection, Equipment Protection and Fast Interlock Systems. Three different technologies to provide protection at three different levels”. Proceedings ICALEPCS 2011 (p. 1055). Grenoble, France.

[4:11] Mark Charlwood et al. “A methodology for the assignment of safety integrity levels (SILs) to safety-related control functions implemented by safety-related electrical, electronic and programmable electronic control systems of machines”. HSE Books, Revised 2004. ISBN 0 7176 2832 9.

[4:12] E. Taurel, et al. “The TANGO control system manual”.

[4:13] A.Götz, E.Taurel, J.L.Pons, P.Verdier, J.M.Chaize, J.Meyer, F.Poncet, G.Heunen, E.Götz, A.Buteau, N.Leclercq, M.Ounsy, “TANGO a CORBA based Control System”, Proceedings of ICALEPCS 2003, Gyeongju, Korea

[4:14] S. Rubio-Manrique, G. Strangolino, M. Ounsy, S. Pierre Joseph. “Validation of a MySQL archiving system for the Alba Synchrotron”, Proceedings of ICALEPCS 2009, Kobe, Japan.

[4:15] S. Rubio-Manrique, F. Becheri, D.Fernández-Carreiras, J.Klora, L.Krause, A. Milán-Otero, Z. Reszela, P. Skorek. “Extending the alarm handling in TANGO”. Proceedings ICALEPCS 2011 (p. 63). Grenoble, France.

[4:16] S. Rubio-Manrique, G. Cuní, D. Fernández-Carreiras, G. Scalamera, “PANIC and the evolution of Tango alarm handlers”. Proceedings of ICALEPCS 2017 (p. 170), Barcelona, Spain. doi:10.18429/JACoW-ICALEPCS2017-TUBPL03

[4:17] N. Janvier, J. M. Clement, P Fajardo, G. Cuní, “IcePAP, an advanced motor controller for scientific applications in large user facilities”. Proceedings of ICALEPCS 2013, San Francisco, USA.

[4:18] T. Coutinho, G. Cuní, D. Fernández-Carreiras, J. Klora, C. Pascual-Izarra, Z. Reszela, R. Suñé, A. Homs, E. Taurel, V. Rey. “Sardana, the software for building SCADAS in scientific environments”. Proceedings of ICALEPCS 2011 (p. 607). Grenoble, France.

[4:19] D. Fernández-Carreiras, J. Andreu, F. Becheri, S. Blanch-Torné, M. Broseta, G. Cuni, C. M. Falcon-Torres, R. Homs-Puron, G. Jover-Mañas, J. Klora (on leave), J. Moldes, C. Pascual-Izarra, S. Pusó-Gallart, Z. Reszela, D. Roldan, M. Rosanes-Siscart, A. Rubio, S. Rubio-Manrique, J. Villanueva, T. Kracht, M. T. Nunez Pardo de Vera, T. Coutinho, A. Homs, E. Taurel, V. Hardion, A. Milan, D. P. Spruce, P. Goryl, L. Zytniak, L. Dudek, "Building SCADA systems in scientific installations with Sardana and Taurus". Proceedings of ICALEPCS 2017 (p. 1820). Barcelona, Spain. doi:10.18429/JACoW-ICALEPCS2017-THPHA169

[4:20] C. Pascual-Izarra, G. Cuní, C. Falcon-Torres, D. Fernández-Carreiras, Z. Reszela, M. Rosanes Siscartet, O. Prades-Palacios. "Taurus Big & Small: From Particle Accelerators to Desktop Labs", Proceedings of ICALEPCS 2017 (p. 166), Barcelona, Spain. (p. 166). ISBN: 978-3-95450-193-9, doi:10.18429/JACoW-ICALEPCS2017-TUBPL02, 2018.

[4:21] C. Pascual-Izarra, G. Cuní, C. Falcón-Torres, D. Fernández-Carreiras, Z. Reszela, M. Rosanes, "Effortless Creation of Control and data acquisition Graphical User Interfaces with Taurus". Proceedings of ICALECPS 2015 (p. 1138). Melbourne, Australia.

[4:22] D. Fernández Carreiras et Al. "CCD data acquisition", NOBUGS, Daresbury, U.K, 2000

[4:23] D. Fernández-Carreiras, F. Becheri, T. Coutinho, G. Cuní, R. Homs, G. Jover-Mañas, J. Klora, O. Matilla, J. Moldes, C. Pascual-Izarra, Z. Reszela, D. Roldan, S. Rubio-Manrique, X. Serra. "Synchronization of motions and detectors and continuous scans as a standard data acquisition technique". Proceedings of ICALEPCS 2013. San Francisco. USA.

[4:24] Z. Reszela, G. Cuní, D. Fernández-Carreiras, C. Pascual-Izarra, T. Coutinho. "Implementation of continuous scans used in beamline experiments at Alba synchrotron". Proceedings of ICALEPCS 2013. San Francisco, USA.

[4:25] Z. Reszela, G. Cuní, C. Falcón-Torres, D. Fernández-Carreiras, C. Pascual-Izarra, M. Rosanes-Siscart, "Iterative development of the generic continuous scans in Sardana", Proceedings of ICALEPCS 2015 (p. 524) Melbourne, Australia.

[4:26] J. Lidon, D. Fernández-Carreiras, J.V. Gigante, J. Jamroz, J. Klora, O. Matilla, "Low current measurements at Alba", Proceedings of ICALEPCS 2011, Grenoble, France.

[4:27] E. Plouviez, F. Epaud, L. Farvacque, J.M. Koch "Optimisation of the SVD treatment in the fast orbit correction of the ESRF Storage Ring", Proceedings of IBIC 2013, p. 694, Oxford, U. K.

[4:28] M. G. Abbott, J. A. Dobbing, M. T. Heron, G. Rehm, J. Rowland, I. S. Uzun, S. Duncan, "Performance and future development of the diamond fast orbit feedback system", M. G. Abbott, J. A. Dobbing, M. T. Heron, G. Rehm, J. Rowland, I. S. Uzun, Diamond Light Source, Proceedings of EPAC08, Genoa, Italy.

[4:29] D. Bulfone, R. De Monte, M. Ferianis, V. Forchi, M. Lonza, “Fast Orbit Feedback Developments at Elettra”, Proceedings of EPAC 2004, Lucerne, Switzerland.

[4:30] L. Tanner, F. Jenni, “Digital control for highest precision accelerator power supplies”, Proceeding of PAC-01, Chicago 2001.

[4:31] X. Serra-Gallifa, S. Blanch, D. Fernández-Carreiras, A. Gutiérrez, Z. Martí, O. Matilla, J. Moldes, A. Olmos, R. Petrocelli, ”Fast Orbit Feedback Implementation at Alba synchrotron“. Proceedings of ICALEPCS 2013. San Francisco. USA.

[4:32] A.Olmos, J. Moldes, S. Blanch, X. Serra, Z. Martí, R. Petrocelli, “First steps towards a fast orbit feedback at Alba”. Proceedings of IBIC 2013, Oxford, U.K.

[4:33] D. Beltran, I. Costa, A. Camps, D. Fernández-Carreiras, J. V. Gigante, J. Klora, O. Matilla, V. Prat. “Alba Control and cabling database”. Proceedings of ICALECPS 2009 (p. 423). Kobe, Japan.

[4:34] S. Rubio-Manrique, D. Beltran, I. Costa, D. Fernández-Carreiras, J.V. Gigante, J. Klora, O. Matilla, R. Ranz, J. Ribas, O. Sanchez, “A bottom-up approach to Automatically configured TANGO Control Systems”. Proceedings of ICALEPCS 2011, Grenoble, France.

[4:35] Z. Reszela, G. Cuní, C. Falcón-Torres, D. Fernández-Carreiras, G. Jover-Mañas, C. Pascual-Izarra, R. Pastor-Ortiz, M. Rosanes-Siscart, S. Rubio-Manrique. “Bringing quality in the controls software delivery process”. Proceedings of ICALEPCS 2015 (p. 485) Melbourne, Australia.

[4:36] V. Bobillier, S. Haas, M. Joos, J. Mendez, S. Mico and F. Vasey. “MicroTCA and AdvancedTCA equipment evaluation and developments for LHC experiments” Topical Workshop on Electronics for Particle Physics 2015, September 2015, Lisbon, Portugal. doi:10.1088/1748-0221/11/02/C0202

5 DETECTORS AND SPECIFIC DATA ACQUISITION SYSTEMS

Beamlines have specific needs in terms of diagnostics, and in particular detectors and experimental data acquisition. The detectors field is multidisciplinary and particularly broad. Depending on the application, specific characteristics are required such as special resolution, energy discrimination, temporal resolution, quantum efficiency or frame rate. Solid-state detectors such as CCD[197] cameras or more recent CMOS[198] sensors and Pixel Array Detectors (PADs[199]) are adapted to different applications, from diffraction to X-ray absorption, imaging or tomography. One of the requirements more developed in the last years is the data acquisition speed, in particular in two-dimensional detectors. Photographic films were popular until the nineties, they had a very good quality, a good signal-to-noise ratio, but they obviously had the important drawback related to data acquisition speed. The CCD cameras took over, much faster, but with a big room for improvement in different aspects. In the first years, they were optimized to maximize the signal-to-noise ratio to the detriment of the data acquisition speed. Most were originally conceived for astronomy, designed as back-illuminated in order to increment the quantum efficiency. The integrated circuit can be cooled down to -80ºC by a Peltier device [5:1]. Their readout time was in the order of seconds although this could be increased with a proper region of interest or binning[200].

Some techniques required a faster rate to study time resolved events. Techniques such as SAXS[201], studying different reactions of the sample to an external event required a minimum of tens or even hundreds of images per second. Gas filled multi-wire detectors (MWPC[202]) [5:2] [5:3], were initially developed at CERN in the sixties and in the nineties adapted to synchrotron radiation applications such as SAXS (Small Angle X-ray Scattering), protein crystallography and many others. Nowadays they are very popular for their versatility, energy discrimination, low noise and data acquisition speed.

5.1 Diffraction and two-dimensional detectors

A diffraction image has typically a collection of brilliant spots in a sort of uniform background, or depending on the technique, they could also be arranged in circles. As an example, in a non-

---

197 CCD: *Charge-coupled Device*: Integrated circuits adapted and popularized for the image acquisition.
198 CMOS: *Complimentary Metal-Oxide-Semiconductor*. Integrated circuits manufacturing technology optimized for a high level of integration and low consumption.
199 PAD. *Pixel Array Detectors*. CMOS based detectors designed for X-rays, usually photon counters and which include energy discriminators that drastically reduce the noise in a wide range of experiments.
200 "*Binning*" consists of grouping pixels in the detector (for example a CCD) in a way that two or more pixels are read and digitalized together reducing the size of the image and increasing the acquisition in the same proportion.
201 SAXS: *Small Angle Scattering*: X-ray diffraction oriented to small angles typically requiring a 2D detector located far away from the sample, in order to increase spatial resolution.
202 MWPC: *Multi Wire Proportional Chamber*. Detector made of a succession of micro-wires in both planes and in presence of an ionized gas to induce an electrical current in the wires in presence of a photon of a certain energy.

crystalline diffraction pattern, a peak corresponds only to 10^{-7} of the incident flux with a signal-to-noise ratio of about r=5. This means that we need at least 10^{11} photons per second per mm^2; or in other words, 10^{13} photons per second per mm^2 for a time resolved experiment taking 100 images per second [5:4]. Third generation synchrotrons offer that flux and therefore allow time-resolved experiments when the detector follows. The detector requirements depend much on the application.

An ideal detector:

- Does not have dark current
- Has an infinite dynamic range
- Has a 100% Quantum Efficiency
- Does not have dead pixels and all pixels have exactly the same behavior without noise
- Has a very high frame rate (infinite)
- Has a very high spatial resolution
- Has a very high number of bits
- Very low power consumption
- Very low manufacturing cost
- (from the point of view of the facility is free and from a company's point of view it has a very high price (profit))

Of course, these requirements need to be refined and compromised. For example, typical diffraction experiments require at least spatial and temporal resolutions in the ranges shown in Table 8.which are currently (2019) met by a number of technologies and manufacturers.

Spatial resolution	**150 µm x 150 µm**
Number of pixels	> 1000 x 1000
Dynamic range and counting rates	10^5 counts /mm^2/s
Dynamic range in the whole detector	>10^8 Hz
Sensitivity[203]	1 photon / pixel
Energy	~10 keV
Data acquisition speed	Hundreds of images per second

Table 8: Generic requirements for a X-ray diffraction detector.

MWPC detectors show high performance and adapt well to diffraction experiments. However, they are often difficult to operate and need a lot of maintenance. Therefore, since early 2000 they have been progressively replaced by other technologies in particular solid-state based such

[203] *Sensitivity*: Measure of the response of the detector to changes in the input signal.

as the PAD, also photon counting, but more flexible, much more robust and easier to operate and maintain. CMOS (integrators) are suitable for a wide range of applications because of their (relatively) low cost and high frame rates. CCDs (also integrators) are still used given their versatility, low noise and suitability[5:6]. CCDs are silicon chips that naturally detect X-rays and therefore are used for direct detection of soft X-rays (low energies in the range of hundreds of eV). CCDs are also used for hard X-rays (ranges of a few keV and above), usually coupled to a scintillator (the silicon chip is too thin and therefore not efficient at higher energies and sensitive to radiation damage). The scintillators of different materials depending on the application convert the X-rays in visible light that is then detected by the CCD sensor. The scintillator screens are integral part of the detectors conditioning the behavior, spatial resolution, time response, noise [5:5] etc. CCDs used to be slower than MWPC, although more compact robust and easier to maintain. In addition, CCDs recently improved considerably the acquisition speeds by multiplexing the readout channels, increasing sampling rates etc. The CMOS and the PAD detectors are also widely used as they are performing, robust and easier to operate and maintain.

MWPCs are no longer very popular in use in Synchrotrons because of their maintenance, reliability and robustness problems.

5.2 Working principles

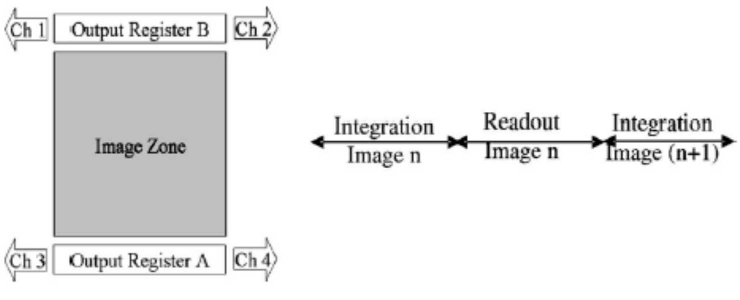
MWPC detectors consist of a gas filled chamber (a mix of a noble gas with another one), with an array of electrodes (wires). The gas absorbs the incident X-ray photons and emits photo-electrons. The number of produced electrons depends on the gas and is proportional to the energy of the incoming X-ray photon. Argon or Xenon produce typically an ionization (electron) for each 30 eV, therefore in the order of 300 for 10 keV incident photons: ten times less than the Silicon. However, the MWPC avalanche effect due to the electrical field in the gas amplifies the charge up to a million times[204], producing signals large enough to detect photons with a high special resolution and a certain spectral resolution [5:4].
The readout electronics may be a delay line or parallel readout. Delay lines are simpler and more cost-efficient but with slower readout, requiring a small number of amplifiers and discriminators but still need a TDC (*time-to-digital converter*), that determines the coordinates of the impact to be stored in the histogram.

The parallel readout requires a preamplifier and discriminator in the cathodes of each wire, in order to process all at once in parallel before accumulating in the histogram. The noise of the detector is dominated by spontaneous emission of electrons in the gas and depends on the

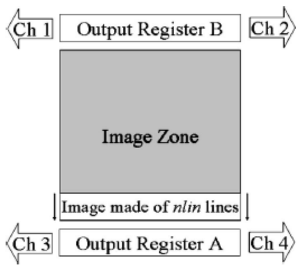
[204] Depends of the combination of gasses. Typically, a noble gas such as Xenon with a percentage of a moderator gas (quench) such as CO_2, in proportions in the order of 80% / 20% [[5:3]].

manufacturing process of the detector, typically tens of counts per second in the whole detector or 10^{-5} per pixel for a one Mega-Pixel detector. This is well known since many years and has been studied and explained with details in diverse literature given at the end of the chapter [5:2][5:4][5:5].

CCD sensors are analogue devices that accumulate charges during the integration time, which then are transferred analogically to the readout register to be digitalized with an ADC. This process can be parallelized including several readout registers and ADCs (Figure 5-1.A). The vertical and horizontal synchronizations could eventually be adapted to specific experiments. The higher flux of newer synchrotrons fostered time resolved experiments with higher frame rates. The CCD technology worked out new integrated circuits to speed up the process. The *Frame Transfer* technology reserves a double area with double number of pixels in the dark (masked from light) where the frame is quickly transferred and from where it can be readout and digitalized while the next exposure takes place, making the process almost continuous when the exposure time is similar to the readout time. In the same sense, the *Kinetics* mode generalizes the Frame Transfer concept where the dark area can be configured and multiplied, keeping several of them in the chip and speeding up the acquisition of these number of frames (the area of the chip used for storage shall be accordingly masked out from light). In some sense this can be seen as a variant of a region of interest with some extra restrictions (typically only possible on the horizontal plane) and optimized for a very fast charge transfer and data acquisition rates. The result is that several exposures can be made in a smaller area of the chip with a very high frame rate (µs rates: the time to move analogue charges, because the whole sequence happens before the digitalization, a much slower process requiring several ms. Figure 5-1.B [5:7]).



(A)



(B)

Figure 5-1 (A): Full frame multichannel readout (4 channels). (B): Kinetics mode readout. Several exposures coexist in the same chip and are later readout together (Ref. [5:7]).

CCD sensors and in particular the scientific grade CCD, designed for scientific applications are expensive. The CMOS technology has shown a great potential, it has rapidly expanded to the large-scale consumer sector (such as mobile phone cameras for example) and is consolidated as an alternative to the CCDs in scientific applications as well.

The main functional difference between CCDs and CMOS sensors is that the latter integrate dedicated transistors per pixel (or group of pixels) for the analogue to digital conversion. Each pixel contains the photodiode and addressing transistors, with an individual amplifier, which speeds up the process but on the other hand introduces an extra noise given by the potential different behavior of different amplifiers of different pixels.
Incident photons generate electron-hole pairs in the semiconductor that translates into a certain current density (A/cm^2); in other words, generate a charge that derives in a current or a voltage that is afterwards digitalized by an ADC.

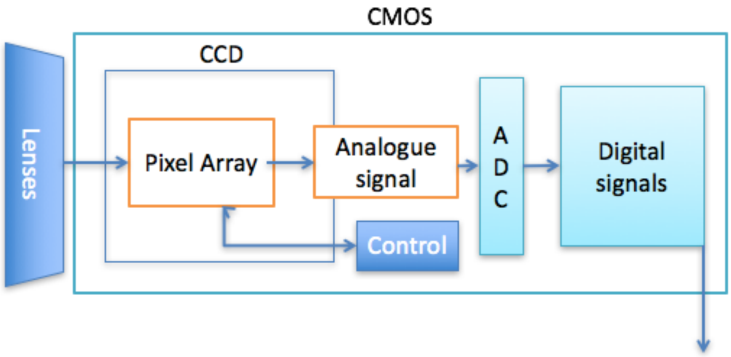


Figure 5-2: Schematics of CMOS detectors versus CCDs

CMOS technologies bring new functionalities in less space, faster and with a lower power consumption. New manufacturing and assembly techniques have made the hybrid Pixel Array Detectors (PAD) possible: *bump bonding*[205] a pixeled sensor[206], a sort of array of photodiodes, with an ASIC in charge of the charge discrimination and the readout of each pixel.
The improvement of the integration level brings the possibility to include new functionalities; for example, the Medipix3 includes dedicated circuits to manage two threshold discriminators and perform a charge ponderation amongst four adjacent pixels to mitigate the undesired effect of the distribution of the charge of the same photon across different pixels [5:9].

[205] Bump bonding or flip chip is a technique that assembles 2 chips connected by purpose specific connection points (“bumps”).
[206] The pixeled sensor is typically Silicon (Si) based, although other materials better adapted to certain energy ranges are used as well. Examples are Cadmium telluride (CdTe) or Gallium Arsenide (GaAs).

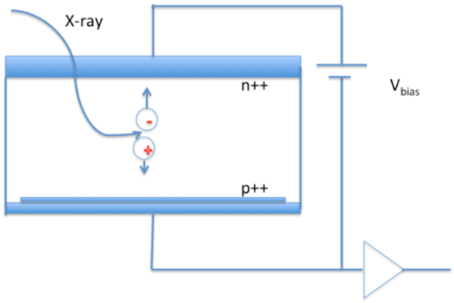


Figure 5-3: Basic principle of a solid-state semiconductor detector

When a photon hits the detector, it is absorbed by the semiconductor material generating a number of electrons depending on the energy of that photon (photoelectric effect). Solid-state semiconductor detectors are usually built on a slightly negatively doped wafer where strongly negative (N) doped and strongly positive doped (P) parts are inserted to create sorts of photodiodes polarized with a bias voltage. The pixel usually absorbs all the photon energy generating a number of electron-hole pairs depending on the energy of the photon and the material. In the case of silicon, a pair is created for each 3.65 eV of the incident photon; hence the charge is proportional to the energy. The equation describing this effect is the following:

$$N_{eh} = h\nu/\varepsilon \quad \text{: Where } \varepsilon = 3.65\ eV \text{ (for Si), } h \text{ is the Plank constant and } \nu \text{ the frequency of the photon.} \tag{1}$$

In some cases, the charge can result divided across several pixels making difficult to distinguish between a high-energy photon and several low energy photons. To mitigate this effect, *adjacent pixels charge adding* is real-time performed by the later detectors such as the Medipix3 as aforementioned.

The discriminators are very convenient in synchrotron applications as photon counting with properly adjusted discrimination thresholds, can reduce the noise to near zero. The proper setup of the thresholds can also minimize the undesired charge sharing effect. Lower thresholds tend to double counting; higher thresholds derive in an effective reduction of the pixel size and consequently the fill factor. Pixel Array Detectors, photon counters with individual electronics per pixel are convenient for moderate incident photon fluxes, such as orders of 10^5 or 10^6 counts per mm^2 per second). However, they saturate with higher fluxes where charge integrators such as CCDs behave better maintaining the linearity.

CCDs are suitable for direct detection as well. A 10 keV incident photon beam would produce more than 2700 electrons per photon, which would even allow counting incident photons[207]. Nevertheless, this is often not feasible at these energies. The limitation of CCDs in direct detection is given by their reduced depletion layer (usually in the order of 20 µm) that corresponds to the absorption depth of photons of up to 5 keV (Silicon). Thicker depletion layer CCDs exist (40 µm) that increase the quantum efficiency, but still not enough for higher energies (10 keV beams would need depletion layers of the order of 100µm not commercially available. Figure 5-4.Right). Direct detection is often used with soft X-rays in the order of few hundreds of eV). CCD cameras are not radiation hard and working at higher energies in direct detection derives in longevity issues, fact that forces the use of scintillator screens of different phosphorescent materials and thickness coupled with fiber optics *tapers*[208] or other optics setups to the CCD/CMOS sensors. The silicon is neither suitable from 20 keV onwards due to the low absorption coefficient (Cadmium telluride (CdTe) or Gallium Arsenide (GaAs) have a more appropriate coefficient for higher energies).

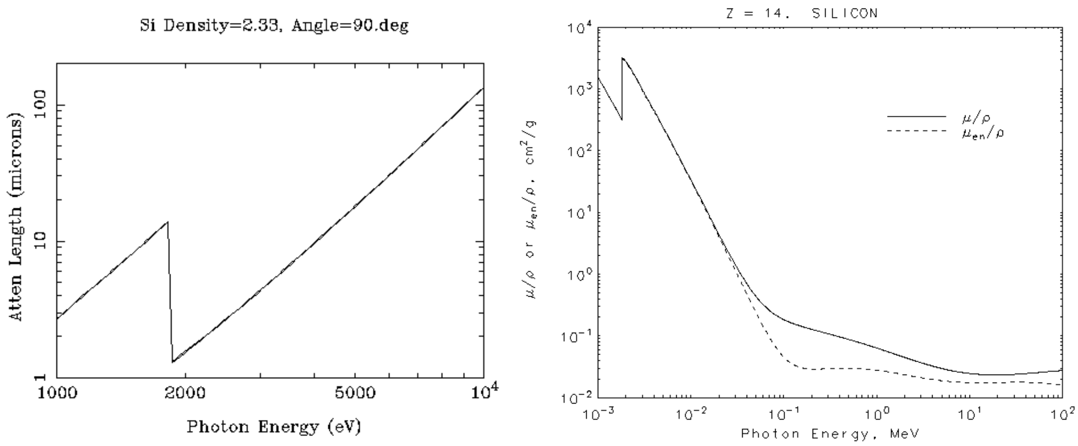


Figure 5-4: (Right) Silicon Attenuation depending on the energy[209]. (Left): Absorption coefficients depending on the energy of the incident photon (source: NIST[210]).

5.3 Detector characterization. Pixel Array Detectors vs CCDs vs MWPC

Pixel array detectors (PAD) are suitable for a number of experiments. Their very low noise (near zero, because of the energy discriminator and the photon counting feature) makes them

[207] The *well capacity* of a CCD is dependent of the chip usually ranging from about 50,000 to 300,000 electrons per pixel. This gives a relatively low dynamic range (in the case of 300,000 electrons per pixel, at 1 keV it would mean 1095 maximum counts per pixel (=300000/(1000/3.65))) that is about 10 bits.

[208] Taper: referred to a fiber optics array that conducts the visible photons from the phosphorescent surface to the CCD sensor. There is usually one fiber per pixel.

[209] http://henke.lbl.gov/optical_constants/atten2.html

[210] NIST: *National Institute of Standards and Technology*. http://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z14.html.

appropriate for experiments where the signal level is low. Multi-Wire Proportional gas filled Chambers count photons and include discriminators as well. They are more suited to moderate incoming flux spread over the surface of the detector to minimize collisions (two simultaneous incoming photons are impossible to distinguish from one of double energy). This happens as well to the PAD, but it can be more critical in the case of MWPC with longer dead times since the readout is carried out by displacing the charges through the wires, columns and rows. High photon fluxes or condensed bunches are better detected by integrators such as CCDs, where the charge is integrated in the well and readout and digitalized at the end of the exposure. In other words every of them have strengths and weaknesses depending on the experiment and data acquisition strategy that are discussed in the next paragraphs.

5.3.1 Noise

Given the nature of the photon counters, both MWPC and PADs have an intrinsic noise close to zero (applying the perceptive corrections, such as defective pixels mask in the PADs, etc.). CCDs show an intrinsic electronic noise from two main sources. The read out noise and the dark current, which depends on many factors such as the working temperature or the intrinsic design of the integrated circuit and results in a few electrons per pixel per second. The electronic noise induced by the amplifiers, the synchronization and the analogue-to-digital conversion and is somehow related to the readout speed. As CCDs are integrators, both sources of noise are reflected in the measurement.

The data acquisition chain foresees a background subtraction integrated in the data acquisition process, with regular acquisitions of the background and the online pre-processing (subtraction) of the acquired image. This has been applied but under highly customized flavors at the different beamlines in the different facilities. The software tools such as SPEC and Sardana discussed in the previous chapter played a key element in this high level of customization.

5.3.2 Gain

The gain is determined by the ratio between the value accumulated in the pixel and the number of incident photons captured by that pixel. In direct detection, the gain is proportional to the absorption coefficient of the material. The gain of a CCD with a scintillator screen will depend on the material of this screen. A typical value is four or more ADUs[211] per incident photon. The intrinsic gain in MWPCs depends on the gas. Greater the atomic number, better the absorption coefficient thus more gain. The next step is given by the gain of the preamplifier.

[211] ADU: *Analog to Digital Unit*. Basic digital unit (that can be distinguished) after the analogue-to-digital conversion stage.

The readout electronics can incorporate several preamplifiers with different gains to increase the readout speed or reduce the noise. This is typically selected from the control system and shall be included in the metadata of the images for the further data analysis.

5.3.3 Spatial resolution

C*rosstalk* is the interaction between adjacent pixels and has a direct impact in the spatial resolution. In a MWPC it is dominated by the parasitic capacitance between wires or micro patterns. In the case of a PAD or a CCD it is given by the charge distribution between adjacent pixels. Other factors such as the parallax errors[212] can also have a contribution in all cases. Some PADs like Medipix3 [5:9][5:11], include operation modes of Charge Summing Modes (CSM)[213], that require specific circuitry to consider 4 pixels (pixel size 110x110 instead 55x55 square microns) to better assign the correct count to the right pixel reducing the *crosstalk*. Scintillators have an intrinsic *crosstalk* due to scattering in the material and an *afterglow*[214] effect, or the remaining luminescence decaying after the excitation. The decay is usually exponential with a small time constant that shall be empirically characterized together with the whole detector setup. The afterglow directly affects the frame rate limits in the form of remaining shadows of the previous image in the following at higher speeds [5:5].

The Modulation Transfer Function (MTF[215]) is a wide and complex concept that can be formally defined as the Fourier Transfer module of the LSF (*Line Spread Function*) defined as the 1D integral of the PSF[216].

$$LSF(x) = \int_{-\infty}^{\infty} PSF(x,y)dy \tag{2}$$

$$MTF = |FFT(LSF)| \tag{3}$$

The MTF describes the capacity of the detector setup to reproduce the original frequencies of the image[217], where a MTF equal to 1 (100%) means a perfect detector.
Both MTF and PSF are related to the efficiency and the resolution of a detection system. While the PSF describes the resolution in the space, the MTF describes the resolution in the spatial

212 Error derived from an incidence angle different from 90 degrees. A photon can be detected by an adjacent pixel.
213 CSM: *Charge Summing Mode.* Designed to improve the effects of charge sharing. Charge is compared and summed between adjacent pixels.
214 Afterglow: Luminescence that remains and slowly decays after an excitation.
215 MTF: Modulated Transfer Function describes how spatial frequencies impact in the data acquisition system. https://en.wikipedia.org/wiki/Optical_transfer_function
216 PSF: Point Spread Function. Describes the system impulse response. https://en.wikipedia.org/wiki/Point_spread_function
217 In colloquial terms is assimilated to a measurement of the contrast.

frequency (pair of lines per mm). For example, an original image of a sinusoidal wave detected with a detector setup with MTF=1, the original wave should remain unchanged with the whole contrast. On the contrary a setup with a MTF equal to 50%, 20% or 10% gets a contrast severely attenuated.

In other words, the MTF can be seen as a measurement of the bandwidth of a detector setup and its efficiency on different frequency ranges. It is used as a figure of merit of spatial resolution. Many different ways to measure the MTF are found in the literature, for example taking an image of an object with a sharp border. The profile orthogonal to the axis is the ESF (*Edge Spread Function*), which derivative is the LSF, and which Fourier Transform magnitude gives the MTF. The LSF can also be obtained scanning a slit in one direction or even applying a 2 dimensional Fourier Transform to the PSF.

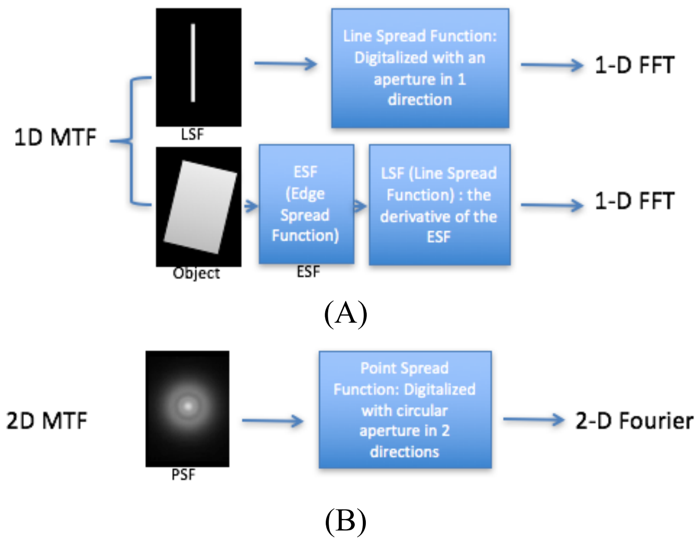


Figure 5-5: Schematic of the calculation of the MTF for one dimension (A) and two dimensions (B)

These methods cannot be suitable for resolutions of a few nanometers in a detection system, for example in a microscope, where the precision of the slits or the fabrication of a sharp object in the nanometer range is not obvious to solve. Therefore, other solutions are required, such as the method developed for ALBA-BL09 [5:14] that uses a known pattern (Siemens Star) and a complex Fourier analysis.

The *crosstalk*, *afterglow*, and other optical aberrations limit the spatial resolution of the detector setup. The MTF is a measurement of the whole system including lenses, mirrors, filters and of course the sensor. It is a characteristic of the system.

5.3.4 Dynamic ranges and counting rates

The dynamic range is defined as the maximum signal divided by the noise level. The dynamic range for CCD type detectors (integrators) would take into account the well capacity in number of electrons divided by the noise (the sum of all noise sources of the detector setup). For example if a CCD has a well capacity of 100,000 electrons, with a dark current of 0.1 e^{-}/sec and a readout noise of 3 electrons, the dynamic range would be 100000/3.1 =32256, which means 15 bits (2^{15}=32768; $\log_2(32256)$=14,98).

Pixel Array Detectors and photon counters in general, have a dynamic range equal to the size of the counter (typically 16 or 32 bits), because the noise tends to zero if the discriminators are well configured. However, in these cases the limitation comes from the linearity at high frequencies of incoming photons (orders of 10^5 or 10^6 ph/s/pixel). Collisions appear and photons are not properly counted, so the linearity is lost. As aforementioned, photon counters are not designed to detect simultaneous events and although they could detect a saturation and interpolate to simulate to some extent a better linearity, the quality of the data would be anyway concerned. CCDs (integrators) on the other hand can be affected by blooming (the well overflows to the adjacent pixels) when the flux is too high or the exposure time is not properly configured. Certain CCDs offer a protection to blooming by draining the overflowed charges, but in any case, a saturated image by definition has lost information.

5.3.5 Efficiency

The Detective Quantum Efficiency DQE[218], is the capacity of a detector to reproduce the original image with a signal-to-noise ratio relative to an ideal detector. It can be expressed in different ways, such as a frequency response. In the frequency domain, the DQE is defined as the square of the MTF divided by the NPS (*Noise Power Spectra*)[219].
In the space domain, the DQE is the square of signal-to-noise of the output divided by the square of signal-to-noise of the input. In this domain, the DQE is a scalar between 0 and 1 where 1 corresponds to the ideal detector (no noise) [5:5][5:12].

$$DQE = \frac{({}^{S_{output}}/_{\sigma_{output}})^2}{({}^{S_{input}}/_{\sigma_{input}})^2} = \frac{(SNR_{output})^2}{(SNR_{input})^2} \quad (4)$$

Considering that the incident photons follow a Poisson distribution, for N photons, if DQE=a,

[218] DQE: Detective Quantum Efficiency. https://en.wikipedia.org/wiki/Detective_quantum_efficiency
[219] Defined in the international norm IEC 62220-1

$$\left({S_{input}}/{\sigma_{input}} \right)^2 = \left(\frac{N}{\sqrt{N}} \right)^2 = N \tag{5}$$

$$then\ aN = \left({S_{output}}/{\sigma_{output}} \right)^2 \tag{6}$$

This is subsequently used in the online/offline data analysis of the output of the detectors.

In summary, the efficiency means the capacity of the detector to convert incident photons in electrical charges (ionization of a gas or generation of electron-holes in a semiconductor). This is a function of the whole system: detector setup including optics, and sensors, materials, thickness and incoming photon beam characteristics.

5.3.6 Specific considerations about the detectors data acquisition systems in synchrotrons experimental stations

The intrinsic integrative nature of CCDs limit their dynamic range to the well capacity whereas the photon counting such as MWPC and PAD have a deadtime from the detection of one photon to the next, a major limitation for high counting rates. Synchrotrons and more particularly X-ray Free Electron Lasers (XFEL[220]) are very brilliant sources with short bunches resulting in a high probability of collision[221]. The linearity as aforementioned could be to some extend corrected but it is not an option for several orders of magnitude higher flux. They require hybrid techniques integrating incoming photons in packets and counting the number of packets. Nevertheless PADs are still the most preferred choice at synchrotron Beamlines, given their reliability, robustness, maintenance costs and very low effective noise. CCD detectors have been in the market for many years and have an intrinsic readout and dark noise. However they have evolved in many aspects including, quantum efficiency, robustness and speed, and are still very suitable for many synchrotron applications. They configure an initial offset (Figure 5-6), which need to be subtracted during the on-line or off-line data processing.

[220] Free Electron Lasers: Linear particle accelerators with long insertion devices that produce short, coherent and very brilliant X-ray pulses. Examples are LCLS in Stanford, USA, SACLA in Japan, Fermi in Trieste, Italia or the most recent and powerful *European X-FEL* in Hamburg.

[221] Collision: in this context means two photons arriving at the same instant.

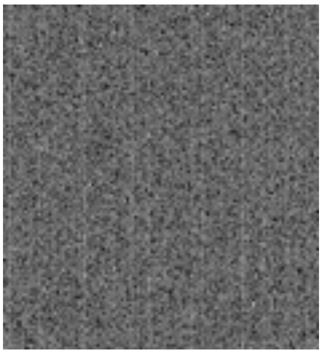


Figure 5-6: Background image given by a CCD camera

PADs on the other hand do not need this subtraction but since they are often formed of stacked modules with a little gap between them that need also to be corrected during the data processing.

Depending on the synchronization schema, CCD detectors can read different channels in parallel or read in frame transfer mode (half of the ASIC is readout while the other half is exposed gathering photons). The data shall be reconstructed accordingly, to harmonize and decouple as much as possible the scientific data analysis from the detector type or model.

5.4 Silicon drift detectors

Energy dispersive X-ray fluorescence (EDS, EDX o XEDS)[222], is a well-established technique to characterize the atomic composition of the sample exposed to an X-ray beam, electrons, protons, etc. When an electron in an atomic orbit is displaced due to an incoming photon, the element emits well energy-defined X-ray characteristic to that particular photon energy and that particular orbit of the electron that allows identifying the element.

The sensor most used for this technique is a solid-state silicon semiconductor that converts incident X-ray photons in electrical charges proportional to the energy. Lithium crystal sensors Si(Li) evolved then into Silicon Drift Detectors (SDD), faster and more robust. SDDs use an electrical gradient created by electrodes in the backside that aim to gather in the anode all charges liberated by the incoming photon. Charges are converted to voltages by a FET[223] transistor and a pulse processor discriminate the energy of the pulse to be assigned to the corresponding channel of the histogram.

[222] Energy Dispersive X-Ray Spectroscopy: https://en.wikipedia.org/wiki/Energy-dispersive_X-ray_spectroscopy
[223] FET: *Field Effect Transistor*.

The resolution relates to minimizing the length of the pulse at half maximum (FWHM), and directly depends on the noise of the preamplifier and the leak currents induced by the bias voltage. Longer processing times result in better precision of the measurement but with a higher deadtime, limiting the counting rate. The collision effect is also present here in form of a pile-up, not discriminating the event but accumulating counts in the wrong energy. The pile-up can be detected to some extent, with a correct characterization of the detector, comparing counting at lower rates, i.e. 1000 counts per second, with higher rates of mega counts per second. Rates of millions of counts per second are a common requirement in today's state of the art X-ray energy dispersive fluorescence stations.
During an experiment, these detectors shall be synchronized with several motions at the Beamline, such as the monochromator, insertion device and other optical and sample environment elements. A continuous scan can involve several SSD detectors, simultaneously combined with others of other kinds. SDD detectors are intrinsically of one dimension per element where the channels are pre-calibrated to energies. Data shall be time-stamped and archived in the central file with the right metadata, which can be challenging when having a certain number of detectors writing simultaneously in the same file.

5.5 Photodiodes

Photodiodes are semiconductor devices (often PIN[224] type) that convert light into electrical charges and therefore current. They have a very broad use, in many places at experimental stations either as monitors or diagnostics and detectors. They are often Silicon built, but other materials can be used depending on the energy ranges (Germanium, Silicon Carbide, Cadmium Telluride, etc.). The operational principle is like the analogue component of integrator detector, working on linear mode with a bias voltage lower than the breakdown voltage. These diodes have a different response to different incoming photon energies and present also dark currents that need to be calibrated. The output current remains proportional to the incoming flux and can be read with a calibrated electrometer.

Photodiodes can also work in avalanche or Geiger mode, where the electron-hole pair is multiplied exponentially until it quenches. These are known as Avalanche Photodiodes (APD), typically used in photon counting mode.

Diodes can also be built on a thin semiconductor layer (10 μm or less [5:15]) very convenient as diagnostic devices that are inserted in the beam with a low attenuation and interference in the experiment. These transmissive diodes are very convenient as monitors of the X-ray beam during the experiment and always available for future normalizations of other experimental channels. For example, monitoring 5 keV beams with 56.5% transmission rate (10 μm thick)

[224] PIN Diode: Semiconductor diode with a non-doped region between the P-type and the N-type regions.

may be overkilling because it is absorbing almost half of the flux, but at 25 keV the transmission rate reaches 99.4% and is no longer a problem (the problem may come from the very low signal and therefore higher noise in the readout).

5.6 Electrometers

Small currents precision readout is a fundamental requirement in the state of the art synchrotrons and several other scientific installations. Diodes, drain currents generated by the X-ray beams, sample electron yields, etc. need a precise fast and synchronized current measurement. Electrometers can read from milliamperes to the picoampere range and below. Electrometers rely often on trans-impedance [4:26] amplifiers on their analogue stage. Once the signal is amplified it can be read with an ADC (up to 18 bits and more) or with a Voltage-To-Frequency converter (V2F[225]). V2Fs are simple to synchronize and integrate in the chain as they are intrinsically integrators read by general purpose counters, but their use is going down in the global market. ADCs have a higher bandwidth and a greater presence in the large-scale market but give only instant values and the integration over an exposure time shall be carried out by software. Depending on the currents to measure, the bandwidth of the electrometer is often restricted to a few kHz[226], or occasionally less than a kHz for very small currents. The first version of the ALBA electrometer included gain ranges from 1 mA with 103 dB[227] signal-to-noise ratio up to 100 pA with the signal-to-noise ratio reduced to 46 dB. These measurements improve considerably at lower frequencies (100 pA reaches a signal-to-noise ratio 74 dB with a 1 Hz low-pass filter)[4:26] This obviously does not work with fast continuous scans acquisitions. It a challenge (prone to errors) because of the difficulty of properly configuring the whole data acquisition chain for the right bandwidth (detectors, monitors, etc. with the right trigger signals, buffers and filters). Every experiment is different from the previous one and needs different instrumentation with different time constraints. The configuration of the triggering modes required by the continuous scans require a high level of flexibility. In order to meet the requirements of the current and future beamlines, ALBA undertook a project to build a new electrometer from scratch (taking advantage of the experience gained with the previous model). MAXIV joined later creating a collaboration. It has been released in 2018 [5:17].

---

[225] V2F: Voltage to Frequency Converter: Each voltage level is represented by a pulse train with a given frequency that is afterwards read with a counter.

[226] Lower the current lower the reached bandwidth. The whole data acquisition chain, such as length, impedance and type of the cables impact also the precision of the measurement and the maximum bandwidth.

[227] The signal to noise is also represented in decibels (dB). For example 60 dB corresponds to 1000, because 60 = 20 log (S/N) => 3=log(S/N) => 10^3 = S/N = 1000

5.7 Detectors data acquisition systems

As discussed in chapter 4, a synchrotron experimental station integrates several detectors simultaneously. They can be classified as scalars or zero-dimension (0D) such as a counter channel, or an electrometer readout; of one dimension (1D) such as a Multi-Channel Analyzer coupled to a SDD giving spectroscopic information or position sensitive detectors giving spatial information; and bi-dimensional (2D) such as CCD cameras, PADs, etc. Other dimensions can be added such as time (the number of dimensions can be generalized to N). Some experiments require the simultaneous use of several detectors. The participating detectors and channels, as well as the ones to be idle during the acquisition shall be properly configured. The data acquisition software shall foresee the simultaneous data acquisition, synchronization and visualization. The incoming data shall be represented in a coherent and homogenous way. A MWPC and a CCD do not have technologically much in common but both produce 2D images looking similar to the user and to the data analysis software. The data acquisition system shall handle that complexity.

The interface shall be standardized. Although this could be apparently shared by several institutes, the fact is that mostly due to singularities in the data acquisition middle layers and the difficulty for coordinating international overseas collaborations, several implementations have been developed in different institutes across the years. At the ESRF in the early 2000s, a standard detector interface was included in SPEC; a set of standard macros was created to that purpose and specific TACO[228] *device servers* following the standard interface were developed for that purpose. That interface (appendix A) has been used for many years in many Beamlines but mostly at the ESRF; still, the common interface makes possible reusing software from one Beamline to another, sharing detectors and consequently reducing the effort to develop software for new detectors.

The software, as well as the interface shall also be standardized. Configuration and management of memory buffers, online data processing, statistics, etc. are common to most detectors. A shared library with a proper class structure can reuse a great part of the code implementing plugins or other means to include the specific hardware access protocol of that particular detector. A first prototype implementing a buffer management, regions of interest, binning, kinetic modes etc. was implemented in C++ and initially tested in the framework of the ESPIA project with different models of FReLoN cameras [5:7].

[228] TACO. Middle layer developed at the ESRF in the early nineties and based on RPC.

```
#Revision 4.5  2004/01/09 17:18:36  fernande
#macros ls pwd etc were removed
#
#Revision 4.4  2003/11/07 15:24:58  fernande
#little bug showing private config when multiples cameras fixed
#
#Revision 4.3  2003/08/21 18:00:20  fernande
#Gilles berruyer added Concatenation Saving mode in scans
#Saves a single file with all the frames at the end of the scan
#macros _unix and _newunix were removed
#
#Revision 4.2  2003/05/20 17:34:57  fernande
#bug fixed in the sixth argument of the macro ccdintegr .
#
#Revision 4.1  2002/04/11 11:10:18  fernande
#new waitacq (shows the image number during a ccdtake)
#
#Revision 4.0  2002/04/11 11:08:16  icntl
#Multi CCD. These macros can manage several CCD devices at the same time.
#
#%DESCRIPTION%
# Gives the user macros to work with the CCD cameras. The main
# problem are the different features of different cameras.
#%DL%
#%DT% Taking images %DD%
#  %DL%
#    %DT% ccdtake %DD% Takes one image. Does not save the image.
#    %DT% ccdtakeall %DD% All ccds configured take one image.
#    %DT% ccdlive %DD% Takes images continiously until ^c is pressed.
#    %DT% ccdsum  %DD% Takes a number of images and sums them up.
#  %XDL%
#%DT% Saving images to disk %DD% This can also be configured from ccdmenu
#  %DL%
#    %DT% ccdnewfile %DD% Defines prefix, suffix and run number for
#                         the files.
#    %DT% ccdsave %DD% Saves the image taken with ccdtake.
#  %XDL%
#%DT% Setting up parameters %DD% CCD cameras must be configured either by
# ccdmenu (interactive and for all ccd devices) or by ccdsetup (can be called
# with arguments and once per ccd device.
#  %DL%
#    %DT% ccdmenu %DD% Configures the general parameters of all CCD devices.
#    %DT% ccdsetup %DD% Configures the general parameters of a particular CCD.
#    %DT% ccdroi %DD% Defines a region of interest
#    %DT% ccdbin %DD% Defines a row and column binning for the camera
```

Figure 5-7: Prototypes of the SPEC macros that implement the standard interface for detector data acquisition.

The Figure 5-8 shows the general schematic of the data acquisition system for the FReLoN camera with the ESPIA board at the ESRF. It implements a client-server architecture where clients are either SPEC or graphical user interfaces connected to SPEC, directly to the Library or more often via a device server (TANGO, TACO or others). The access to the hardware is carried out by the ESPIA[229] card with a high-speed fiber optics link (2.3 Gbps) for the data acquisition and an emulated serial line for the configuration and operation of the detector. The ESPIA card was implemented originally on a PCI-64 bits format, later updated to PCI-Express.

[229] ESPIA: ESRF-SECAD-PCI-Image-Acquisition: See Appendix B for details of the ESPIA card.

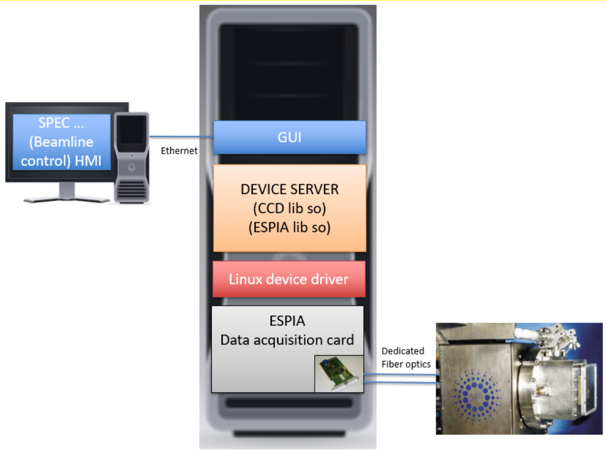


Figure 5-8: Schematic of the data acquisition architecture of the Frelon camera with the ESPIA board (Ref.[5:7]).

The generalization of these prototypes brought a new development: the LIMA project[230][5:8]. It was developed at the ESRF and later used by other institutes such as Soleil and ALBA. The community then helped mostly developing software modules (plugins) for new hardware. LIMA is independent from the operating system and from the control system although it is used mostly in the framework of the TANGO collaboration. The EPICS community, in particular the APS and the University of Chicago developed the "AreaDetector" project aiming to solve the same sort of problems.

AreaDetector and LIMA are projects carried out because of the need of standardization of the detector data acquisition. They have been created from the grounds and previous experience of large institutes such as APS or the ESRF, with extensive experience in 2D detectors and data acquisition systems. They support a wide range of detectors by means of *plugins*[231] that implement the specific access to the hardware. AreaDetector and Lima provide abstraction of generic functionalities to harmonize the differences and particularities of different detectors; a CCD camera is not the same as a PAD, although both produce images, need buffers, can define regions of interest etc. However CCDs often require specific data processing such as *flat field*[232] correction and background subtraction. On the contrary, PADs do not need a background subtraction due to the discriminators with close to zero noise and no offsets, but on the other hand they usually need a geometrical correction to take care of the shade areas in the junction of the different modules, masks for the dead or hot pixels, etc. The common and generic functionalities, memory and buffer management, threads, asynchronous messaging etc. are

[230] A. Homs et Al. Beamline Control Unit, Software Group, ESRF. Grenoble. France.
[231] Plug-in o plugin software component with a well-known interface that extends the functionality of a software application.
[232] "Flat field": defined as the image taken of the beam without the sample to get the imperfections of the optics and the detection system for further normalization (division). Not all techniques allow taking flat fields.

managed in the core and the access to the hardware and specific features are typically managed by the plugins.

	EPICS AREADETECTOR	LIMA
6. Presentation layer. Clients	Clients HMI[233]. GUI[234]: MEDM, CLI[235] : SPEC… etc.	Clients GUI. Taurus, CLI: SPEC, SPOCK, etc.
5. Servers	EPICS Records. In the same way as servers export attributes and process variables on the EPICS Channel Access Asynchronous Communication layer that manages threads and the communication with the devices	Tango Device Servers, Taco Device Servers
4. Core. Memory management 3. Online data processing	Buffer management, Regions of Interest, Binning, Data formats, etc. Online pre-processing, pseudo-counters on images, spatial corrections, background subtraction, flat field correction, etc.	Control Layer. Standardization of data acquisition functions. Buffer management, Regions of Interest (RoIs), binning, Abstraction of functionalities implemented by hardware or software depending on the detector.
2. Plug-ins for several detectors	Classes available for a wide range of detectors. Big community.	Plug-in Layer: ADSC, MAR, FRELON, PILATUS… etc.
1 Device Drivers and hardware access	Hardware API. Interfaces to the manufacturers APIs.	Driver or access to the manufacturers APIs.

Figure 5-9: Detector data acquisition standardization: Area detector and Lima CCD

Acquisition, processing and data presentation of detectors can be modeled in six abstraction layers (Figure 5-9). AreaDetector and Lima consider all six although they are not all always represented.

Level 1 refers to the communication with the hardware. Each manufacturer provides a software configuration and the hardware to communicate with the device. In most cases, this is implemented as a kernel driver including "ioctl" system calls or DMA. It is often complemented with a shared library (.so or .dll) with a well-defined API[236]. This level 1 implements the manufacturer specific protocols and links with libraries or drivers for which no source code is available in many cases.

233 HMI: *Human Machine Interfaces*.
234 GUI*: Graphical User Interface*. A type of human machine interface graphical based.
235 CLI: *Command Line Interface*. Text based interfaces such as SPEC or SPOCK (Sardana).
236 API: Application Program Interface.

Level 2 provides the necessary plugins to communicate with the hardware. Each plugin implements the interface defined by the core and uses the specific APIs and protocols provided by the detector at level 1. Writing a plugin requires basic information of the detector, synchronism mechanisms, commands and protocols to start, stop, read, manage triggers etc.

Levels 3 and 4 refer to the core of the libraries. Usually the level 3 manages online data processing, such as the accumulation of several frames to simulate longer exposure times and dynamic ranges [5:8], the subtraction of the background offsets in a CCD, the correction of the inhomogeneous intensity of the incident beam by dividing by the flat field images of the beam without the sample, etc. Level 4 corresponds to the management of the memory, images sizes, such as regions of interest and binning modes, different synchronization modes such as "kinetics" that may divide the image in different zones acquired with different effective exposures. These settings result in buffers of different sizes with multiple constraints, for example, the regions of interest defined by the hardware in some detectors only can be defined in the center, in one dimension or with even or power of two sizes.

The management of these functionalities provides transparency and simplicity to the upper level software. For example, not all detectors can handle regions of interest whilst others allow defining several of them at once. If a detector does not allow a region of interest, the abstraction layer can provide one handled by software (which does not speed up the data acquisition but reduces the image size and consequently the memory and disks usage).

Level 4 also manages the data storage. There can be different modes and formats involved: keeping one file per image; all images in a series in the same file, stored in one particular format; or more than one file with different formats such as HDF5[237]/Nexus[238], EDF[239],or CBF[240]. Storing the images requires the acquisition process to make the different metadata available to form the headers and store these metadata in the correct formats and appropriated fields.

Level 5 is the Server layer that can be included or managed apart from the standard library. This communication layer can be independent from the lower levels. In the case of AreaDetector and Lima the layer refers to EPICS and Tango respectively. It manages the asynchronous communication with clients and other servers. AreaDetector manages callbacks using EPICS *async* devices.

---

[237] HDF5: A data model and a data format that provides a set of libraries and tools. https://www.hdfgroup.org/HDF5

[238] Nexus Data format for experimental data, conceived for neutron and light sources and based on HDF5 and XML.

[239] EDF: ESRF Data Format. Data format used at the ESRF and other synchrotrons such ALBA that has a fixed length ASCII header with metadata followed by a binary data encoded. It supports several images in the same file.

[240] CBF: Crystallographic Binary File: Data format extended for protein crystallography with an ASCII header and binary encoded complementary to CIF (Crystallographic Information File) ASCII based.

Level 6 is the presentation level. It covers the client applications, usually the human-machine interfaces. They also include user tools that provide monitoring and configuration of the lower level layers. MEDM graphical interfaces are common in the AreaDetector environment, and human-machine interfaces communicating through TANGO servers in the Lima world (Lima provides access to shared memories in the SPEC format that export buffers and information in different configurations as well).

The homogenization of detectors and data acquisition makes the integration of new detectors easier as well as the maintenance of the existing instruments. There are a number of libraries and tools in different institutes based on different platforms, although synchrotrons in general have moved a step forward in terms of standardization with Lima and AreaDetector as the flagships within the TANGO and EPICS collaborations.

5.8 Characterization and online data processing

Detectors and detection systems in general (including optical elements as well as the sensors and even the source) need to be characterized and calibrated for their optimal operation. Real detectors have inherent limitations (compared to ideal detectors) that need to be considered for the data processing and analysis [5:5]. Among others:

- Spatial Resolution
- Intensity homogeneity (flat field)
- Energy
- Geometrical distortions
- Background subtraction
- Linearity corrections
- Cosmic rays or other spurious points

The spatial resolution needs to be characterized for the subsequent data analysis. The background subtraction and the intensity homogeneity correction are closely related to 2D detectors, in particular integrators such as CCDs. The beam intensity shows imperfections introduced mostly by the optics and the source that are particularly disturbing when studying for example the absorption at the sample. Flat field correction to tackle these problems or background subtraction are common online data processing jobs. The next equation shows a typical operation in an X-ray absorption experiment with a CCD detector:

$$Image_{\ result} = \frac{Image_{acquired} - Image_{background}}{Image_{flatfield}} \qquad (7)$$

Spatial distortions are produced by image intensifiers, fiber optics tapers to guide photons from the phosphorous screen to the sensor, inter-chip spaces in PAD detectors, etc. This correction is often a good candidate to perform online. Angular corrections are provoked by the fact that the absorption of photons depends on the incidence angle in both phosphorous screens and sensors.

Linearity corrections apply often to photon counters. Fast counting reaches a limit (typically 1 or 2 MHz depending on the detector) where the relation between incident photons and detected photons stops being linear. In certain cases, and assuming a constant flux in time this can be corrected.

Depending on the instruments and the computing power, a number of these corrections and operations can be accomplished online in order facilitate the visualization and further data analysis. This visualization of raw and preprocessed data is a key requirement in most experimental stations.

5.9 Summary

The standardization and integration of different kinds of detectors, including 0D (electrometers, ADCs, V2F, counters), 1D (Silicon Drift Detectors (SDD) or any Position Sensitive by means of AreaDetector, Lima or other standards is and will be highly strategic. These libraries give response to a rather complex memory, data and detector configuration management and shall be integrated in the control systems and scientific SCADAS. Continuous scans covered in chapter 4 pursuit data acquisition accuracy and efficiency, with a great impact on motion control and flexibility of synchronization, requiring increasingly more precision with more simultaneous detectors and higher bandwidth.

Each experiment, each sample type and each user may need a special configuration and new instruments that need to be integrated with the existing hardware. For example, combining different types of detectors like PADs and CCDs with other kinds such as SDD is often a must. All motors and detectors shall be integrated and be able to be properly configured for the data acquisition and for the proper data visualization from different simultaneous human machine interfaces (graphical and command line). The setup is often carried out and tested in only one day. This is only affordable with modular systems that that fully manage the data acquisition workflow.

5.10 References

[5:1] K. Van Dyke, C. Van Dyke, "Luminescence Biotechnology: Instruments and Applications. CRC Press, 2002.

[5:2] G. Charpak, R. Bouclier, T. Bressani, J. Favier and C. Zupancic, "The use of multiwire proportional counters to select and localize charged particles", Nucl. Instr. and Meth. 62 (1968) 262.

[5:3] F. Fernández, I. Ramos-Lerate, J.C. Martínez, D. Beltrán, J. Bordas and M. Key. "New Micro Pattern Gas Detector Based on a 2D Position Readout Mesh". Instruments and methods in Physics Research, pp 298-301 (2007).

[5:4] J. Helliwell, P. Rentzepis, "Time-resolved Diffraction", Oxford University Press, 1997.

[5:5] S. M. Gruner, M. W. Tate, E. F. Eikenberry, "Charge-Coupled device area x-ray detectors". Review of Scientific instruments, 73/8, 2815-2848, 2002.

[5:6] M. Di Michiel, J. M. Merino, D. Fernández-Carreiras, T. Buslaps, and V. Honkimäki, P. Falus, T. Martins and O. Svensson. "Fast microtomography using high energy synchrotron radiation" Review of scientific instruments, 76, 043702, 2005.

[5:7] J.-C. Labiche, O. Mathon, S. Pascarelli, M. A. Newton, G. G. Ferre, C. Curfs, G. Vaughan, A. Homs, D. Fernández-Carreiras. "The Frelon camera as a versatile x-ray detector for time resolved dispersive EXAFS and diffraction Studies of dynamic problems in materials science, chemistry, and catalysis". Review of Scientific Instruments 78/9 2007.

[5:8] A. Homs, L. Claustre, A. Kirov, E. Papillon, S. Petitdemange, "LIMA: A generic library for high throughput image acquisition", Proceedings of ICALEPCS 2011, Grenoble, France.

[5:9] R. Ballabriga, G. Blaj, M. Campbell, M. Fiederle, D. Greiffenberg, E.H.M. Heijne, X. Llopart, R. Plackett, S. Procz, L. Tlustos, D. Turecek ,W. Wong, "Characterisation of the Medipix3 pixel readout chip", JINST 6 C01052 (2011).

[5:10] C. Ponchut, J.M. Rigal, J. Clement, E. Papillon, A. Homs, S. Petitdemange, "MAXIPIX, a Fast Readout Photon-Counting X-Ray Area Detector for Synchrotron Applications", JINST 6 C01069 (2011).

[5:11] T. Poikela, J. Plosila. T. Westerlund, M. Campbell, M. De Gaspari, X. Lloart, V. Gromov, R. Kluit, M. Van Beuzekom, F. Zappon, V. Zivkovic, C. Brezina, K. Desh, Y. Fu, A. Kruth. "Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout". International workshop on radiation Imaging Detectors. Paris France (2013)

[5:12] C. Ponchut, F. Zontone, H. Graafsma, "Experimental Comparison of Pixel Detector Arrays and CCD-Based systems for X-Ray Area Detection on Synchrotron Beamlines", IEEE Transactions on nuclear science, 52, 1760-1765, 2005.

[5:13] W. C. Phillips, M. Stanton, A. Stewart, H. Qian, C. Ingersoll, R. M. Sweet, “Multiple CCD detector for macromolecular X-ray crystallography”, Journal of applied Crystallography. 33, 243-251, 2000.

[5:14] J. Otón, C. Sorzano, R. Marabini, E. Pereiro, J. Carazo. “Measurement of the modulation transfer function of an X-ray microscope based on multiple Fourier orders analysis of a Siemens star”. Optics express, 23 (8), 2015.

[5:15] C. Cruz, G. Jover-Mañas, O. Matilla, J. Ávila, J. Juanhuix, G. Pellegrini, D. Quirion, J. Rodríguez, “10um thin transmissive photodiode produced by Alba synchrotron and IMB-CNM-CSIC”. Proceedings of iWoRID 2014, Trieste, Italy.

[5:16] J. Lidon, D. Fernández-Carreiras, J.V. Gigante, J. Jamroz, J. Klora, O. Matilla, “Low current measurements at Alba”, Proceedings of ICALEPCS 2011, Grenoble, France.

[5:17] J. Avila-Abellan, M. Broseta, G. Cuní, O. Matilla, M. Rodríguez, A. Ruz, J. Salabert, X. Serra-Gallifa, ALBA-CELLS Synchrotron, Cerdanyola del Valles, Spain. “EM# Electrometer comes to light”, Proceedings of ICALEPCS 2017, p- 137, doi:10.18429/JACoW-ICALEPCS2017-TUAPL04, Barcelona, Spain.

[5:18] D. Fernández Carreiras et Al. “CCD data acquisition”, NOBUGS, Daresbury, U.K, 2000

6 SERVICE MANAGEMENT AND MAINTENANCE

Once the construction and the commissioning are completed and the facility turned to operation, the maintenance procedures become a critical success factor, involving the operation schedule, programmed shutdowns, stock management, etc. Each component has an estimated lifetime and requires a specific maintenance plan. Some values defined in the technical specification first, and in the technical documentation afterwards, such as MTBF[241], are used to design maintenance plans and procedures and define service levels. But the overall task is much greater involving not only hardware: instruments, cables, connectors, etc., but also software: operating systems, control system software, IT infrastructure and in general all components in the infrastructure of the installation.

6.1 Maintenance strategies

The appropriate maintenance of the installation is critical to keep assets, instruments and services in optimal operational conditions. The installation needs a maintenance strategy to ensure the correct delivery of services along the years. Conventional installations such as air conditioning, often rely on external contractors because of the size of the market and the standards of the industry offer suitable turnkey options for most cases. However, the maintenance of the particle accelerator and Beamlines require specific knowledge and often internal resources an only well-defined specific tasks are to be outsourced to external companies. The maintenance covers all components of the installation. The strategy can combine corrective and preventive approaches depending on the subsystem and on the application. Corrective maintenance is performed in emergencies, after a critical failure or in scheduled shutdowns if the severity was limited and the operation was not interrupted. Preventive maintenance is carried out in shutdowns, scheduled according to the number of working hours of the instruments[242] or the data acquired from monitoring key parameters, such as temperatures, vibrations, noise[243], etc. Occasionally some components can be duplicated in a redundant fault-tolerant configuration to mitigate the impact of failures; hard disks, power supplies and even switches or computers are examples of redundancy. These redundant configurations reduce the need for the preventive maintenance as the redundant fault tolerant elements can be replaced when they fail without disturbing the operation. Fault tolerance and redundancy are expensive configurations that are not affordable in the whole installation. Preventive maintenance aims to replace the component before it fails so the operation is not affected; arc detection fiber optics, ceramic parts, bearings, transistors, etc. are other examples of preventive maintained components.

[241] MTBF: Mean Time Between Failures.
[242] Time based Predictive Maintenance
[243] Condition Based Predictive Maintenance

The corrective maintenance is closely related to the service operation. Incidents are registered in the service desk portal. The maintenance of the services and their corresponding infrastructure is a key activity described and documented as processes.

One of the aspects more directly related to the incident management is the management of stocks and spare parts. The appropriate number of spare part stocks and fault tolerant components is key for the service delivery, the cost-efficiency and the overall performance of the installation. There is a lot of literature on this subject [6:1][6:2][6:3], and specifically on the management of stocks [6:4].

Once a failure occurs, an appropriated answer shall be given in due time, registering the incident and coordinating the support teams to get the failure repaired or the instrument replaced. A correct management of stocks of spare parts is key for solving these incidents. Stocks cost money, need space and management efforts. From the financial point of view one would need the minimum number (just in time) to reduce the investment. On the other hand, a reparation delayed because of a missing spare part can cause important loses. The calculation of the items and number of spare parts in stock requires a lot of experience and historical data to achieve a cost-effective result within the boundaries given by the budget. A mathematical model (there are a few in the literature as well) can be added to the decision making process. An example shown in the following equation follows the approach of a Poisson distribution [6:1]:

$$P = \sum_{n=0}^{s} \left[\frac{(K\lambda t)^n e^{-K\lambda t}}{n!} \right] \qquad (1)$$

This equation describes the probability that one spare part is available in stock "P", considering that the overall number of spare parts "s" of a type that is used "K" times in the installation and has a probability of failure "λ" (λ=1/MTBF) and have a delivery time equal to "t".
Following this theoretical Poisson distribution, we can conclude that with double mean time between failures we reduce to half the number of spare parts. Reducing the delivery time we reduce as well the number of stocks. As an example, if we have 1000 parts (K) with 60 days delivery time (t) and a 20 years MTBF, we need 13 pieces in order to have 95% probability of availability of stocks. If we reduce the delivery time down to 30 days, we would only need 8 pieces to ensure the same probability. Reducing the MTBF from 20 to 10 years increases again the number of stocks to 13 in order to keep the same probability.
However, in practical terms there are a large number of cases where the previous hypothesis is not doable, because either the mean time between failures is not known, or there is only one piece in the installation because is too expensive, too big or too specific. So spare parts stock policies result from a compromise between stocks available, cost of the spare parts, time between failures and time to repair.

6.2 ITIL service catalogues

ITIL [6:5], an acronym that stands for Information Technologies Infrastructure Library, compiles a collection of best practices related to service provision. A good practice is a methodology or technique that has been improved from the experience across the years and in different environments and that is proven to optimize the results in a given discipline. ITIL provides a systematic approximation to the development of processes in an Information Technology (IT) department or organization. It defines a service as a way to bring value to the clients delivering the results they need without assuming the ownership of the infrastructure and the costs associated. A service lifetime is divided in five phases: strategy, design, transition, operation and continuous service improvement. Each phase defines a number of processes, functions and roles, as well as the corresponding inputs and outputs. They are all precisely detailed in the official guides such as the official ITIL 2011 published by the OGC (Office of Government Commerce) [6:5]. ITIL is complemented with other norms methods and standards such as PRINCE2[244] [6:6] for project management, COBIT for IT governance, ISO20000 (the ITIL based norm) for service management.
Once the installation and commissioning are completed the whole system turns into operation. The operation of a large scientific installation is formally or de-facto broken down in several services. The following paragraphs cover the services oriented to the control system classified as Primary and Support Services. The general IT services present in the whole organization similar to the existing and documented in the industry are separated in another category. Figure 6-1 shows a breakdown of the main processes described in ITILv3. ITIL describes more than twenty processes in total. Implementing all of them is out of the scope of most organizations. The institution should identify the most important according to its own strategy and define, document and implement these, typically starting by the Service operation (incident, problem, request management), since the ITIL best practices are often adopted when already in operation or late during the construction phase. The red boxes highlight the most critical processes to start with in a running facility.

[244] PRINCE2: PRoject IN Controlled Environments. Project Management Methodology.

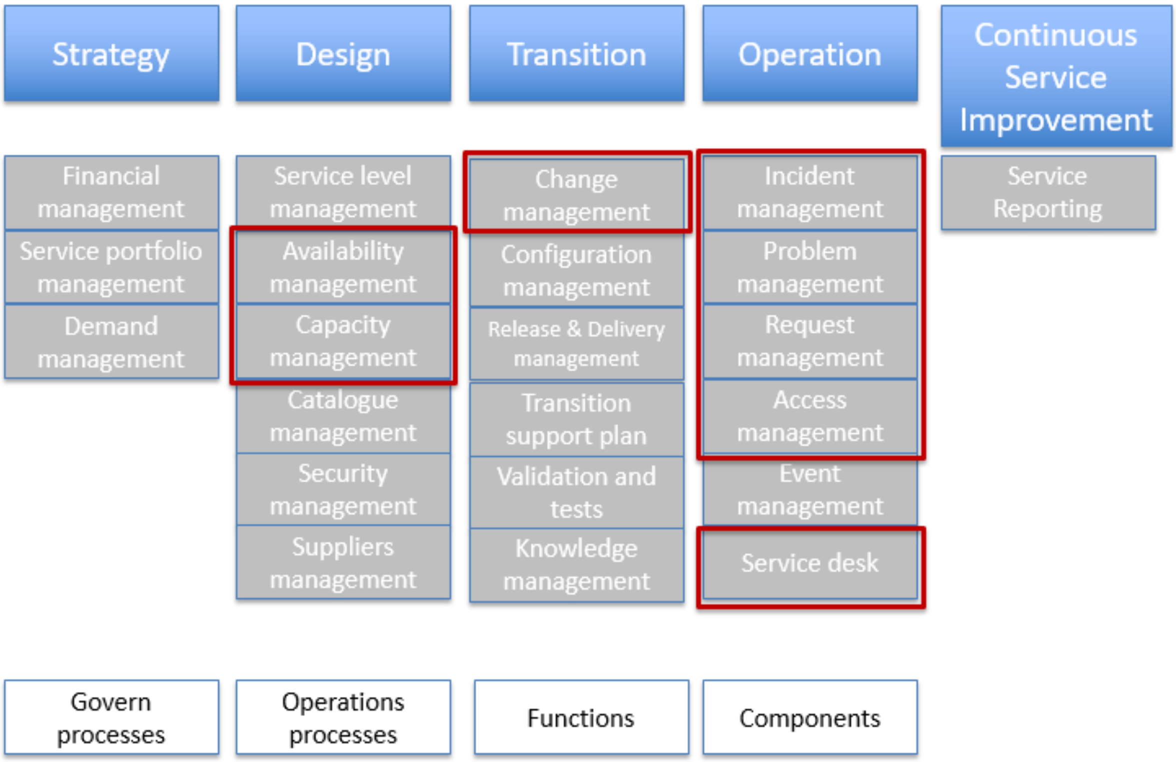


Figure 6-1: ITIL v3 processes [6:5].

6.2.1 General services

The so-called general services give support to the specific Beamline and particle accelerators control system services. These are for example standard IT services such as email, printing, user support etc. common to most organizations.

6.2.1.1 Email, printing, network

The electronic mail service is probably one of the most standard and widely studied. It offers the email service to the clients together with functionalities such as anti-spam managing grey, black and white lists, antivirus, configurable filters, etc. It is a candidate to be outsourced because of its low specialization and added value and the possibility of reducing costs, although keeping into account the cons of the outsourcing such as the loss of knowledge, privacy, control…

Like email, there are a number of generic IT services, well known and common to all organizations that as well are good candidates to be externalized. These are for example, printing, network infrastructure, service desk, user support…

6.2.1.2 PC personal computers, server hosting, application hosting, licensing, storage, backup, archive, high performance computing clusters and others.

The same as the aforementioned email, printing and network, there are several others well known in the industry such as hosting, storage, backup, computer clusters, etc. that can be as well considered as commodities and outsourced. However, every one of them may have particular constraints, such as data volumes, bandwidth requirements, data privacy, security or others that prevent it from being externalized.

6.2.2 Particle accelerator control and data acquisition systems

This is the general service for the control systems of the particle accelerators. It provides access to the instrumentation, monitoring, trending archives and charts, etc. It ensures the correct operation of the installation and must be operational 24x7[245] because it provides access to setpoints, diagnostic and monitoring data, alarms, interlocks etc. It includes hardware and software for the supervision and data acquisition, as well as human machine interfaces for operators and support for the related subsystems.

6.2.2.1 Description

The project of the control and data acquisition system once developed, installed, deployed and commissioned is transitioned into a service. This is the specific IT service for particle accelerators that is described in the following paragraphs. It includes the subsystems of the particle accelerator and uses most general IT services such as network, server and application hosting, software asset management, as well as generic control system services such as motor control systems, equipment databases, equipment and personnel protection systems, etc.

6.2.2.2 Characteristics

Some aspects of the implementation can substantially change from one institute to another; however, there are several elements and structural components following a common approach. The supervision, control and data acquisition of vacuum systems, power supplies, radiofrequency, diagnostics and synchronization are subsystems present in all particle accelerators. Depending on the size and characteristics, they can be more or less large and complex. The general function of the control system is to provide the needed services for the operation in terms of supervision, visualization, diagnostics and data acquisition, giving centralized access to all remote components of the subsystems. These services are used by the operators and the machine physicists and rely on an appropriated hardware and software infrastructure.

The control system also includes infrastructure to protect components and personnel from an eventual failure or malfunction, interlocks, alarms, alerts, reports, archives and fast data loggers

---

[245] 24 hours a day, 7 days a week. In this case with some exceptions: The scheduled shutdowns are used to fix errors deploy new functionalities, correct issues or upgrade parts of the system

to perform postmortem analysis. In short, the control system is a structural component of the installation. The alternative could be not giving a centralized service but all subsystems would implement their own, with the obvious problem for the maintenance and the operation of the system. In a more and more competitive environment, the control system requires homogeneous and standardized hardware and software to be cost-effective in terms of construction budget, overall performance and maintenance costs. Standards make simpler to share knowledge within the teams[246], the stock of spare parts smaller, simpler to manage and cheaper. The **scope of the service** is difficult to specify, since it depends on the strategy of the facility and on the organization of the support groups. It also depends on the operational budget and on multiple external factors.

6.2.2.3 The scope includes

The analysis of requirements of subsystems, purchasing of infrastructures and call for tenders, project plans, and of course the development, installation, commissioning, operation and long-term maintenance. For example, a particle accelerator of a synchrotron typically includes interfaces for Insertion Devices, radiofrequency control, equipment protection, human machine interfaces, synoptics, recipes and archivers, diagnostics, with various systems such as beam position and beam loss monitors, Analog to Digital Converters (ADCs) and oscilloscopes for various signals, readout and control of fluorescence screens, control systems for the vacuum elements, power supplies etc.
The ultimate motivation of the “accelerators control system” is the integration of the aforementioned subsystems and their components in a whole, making it robust and to some extend compact given the overall size and the number of subsystems.

6.2.2.4 The scope excludes

The accelerator control system service typically excludes the control system for the general infrastructures, HVAC[247], cooling systems with deionized water, nitrogen, compressed air, power distribution, etc. It also excludes the development of correction algorithms and accelerator physics studies and procedures. Depending on the organization of the institute, part of the instrumentation, very specific to the particle accelerators, can be managed by specialized groups, such as for example the radiofrequency phase and amplitude regulation system among others. The excluded systems involve specific hardware and software and, in all cases, require a detailed definition of the interfaces.

---

[246] People management refers to the wider sense of the term. Mitigating inherent risks to champions, super-heroes or experts that only they have the technical knowledge of a critical part of the system and the consequent impact of their absences. Managing teams to provide a 24x7 service with on call requirements need the team to have a transversal knowledge of the given system in order to be able to give an appropriate response to virtually any kind of incident.
[247] HVAC: Heat Ventilation and Air Conditioning.

6.2.2.5 Service level

A particle accelerator works often 24 hours a day 7 days a week. An operation calendar is normally in place. In the case of synchrotrons, calendars schedule typically 6000 hours per year of operation of the machine, resulting in around 5000 hours per year delivered to the Beamlines and the rest devoted to studies in the accelerator, commissioning, startup procedures, and other ancillary tasks. The plan includes often two long shutdowns (3+ weeks) one in summer and other in winter (for example August and January). One day a week is devoted to changing experiment setups at the Beamlines and Machine studies or maintenance interventions. Short shutdowns (1 week) are also scheduled every four or five weeks. This strategy is shared by the main synchrotrons across Europe and in the world: ALBA, Soleil, Diamond, ESRF, Elettra, PetraIII etc. These short or long shutdowns are used to update services, deploy changes and maintain the service performing planned tasks. The service level agreements can change depending on the conditions, budgets or overall strategies.
The control system is designed as any other service to meet the requirements, maximizing the output minimizing the costs. The service level in terms of availability of the beam is typically 98% or 99%. Failures resulting in a beam loss are then limited to 50 hours a year (1% of 5000, in the case of assuming 5000 hours to be delivered and 99% availability)

It is not common to find formal *Service Level Agreements* (SLAs) although the quality of the service is a strategic critical success factor. The subsystems may include redundant instruments keeping in mind the cost efficiency and depending on how critical they are to the service provision. At the same time, systems are designed to be safe and therefore in many cases redundancy is implemented as fail-safe designs, rather than high availability. This is the typical case of the protection systems that use redundant contacts, relays, cables, and instruments to provide safety (confirmation of any event or action by 2 different channels). There are other cases where redundant components are configured for high availability and make the maintenance easier. This is the case for example of the hot plug double power supplies in computers and PLCs. Unfortunately, most of the equipment and instrumentation cannot be duplicated for budget reasons. As an example, the power supplies for the magnets are many and statistically among the less robust[248]. They provide hundreds of Amperes (AC and/or DC) with a high stability in the order of few parts per million. Most facilities cannot afford duplicating these instruments.

Systems that need a high performance and availability are identified at the design phase. We will identify them as Class A. They can be critical for the whole installation, for example the network, the IT infrastructure hosting critical services or the vacuum system that in case of failure may provoke a long shutdown for repairing. They can include double power supply and

[248] Failures provoking a beam loss are statistically related mostly with Radiofrequency components and power supplies.

are connected to a UPS[249], which improves the availability and the maintenance procedures. The control system computing infrastructure can in many cases run in virtualized servers with the fault tolerance given by the hypervisor. The vacuum system provides chambers divided in sectors with valves controlled by the Equipment Protection System ready to isolate one sector from the next and preventing an accidental venting in a sector propagating to other sectors.

In short, despite of several fault tolerant configurations, there are many parts that can fail killing the beam (outage in the service). In case of critical failure, for example when the beam is lost or if there is a component inside the bunkers that needs to be replaced and the accelerator needs to be stopped, the service is interrupted (no beam) for at least the minimum stopping time[250]. Non-critical failures[251], do not require to stop the accelerator and therefore the service is not interrupted. They usually involve an entry in the *logbook*, which will derive into a ticket (incident) in the service desk and the subsequent work order.

A classification of the systems depending on the criticality is given here as an example. This is directly related to the requirements of each installation but generally, they share a number of common characteristics and requirements:

- **Class A. High performance**:
    - Redundant components configured as fault tolerant. Double power supplies connected to UPS, double network connection for redundancy and a third for monitoring purposes. Standardization of the components after an internal certification, minimizing the variety of hardware and improving the maintenance procedures.
    - Hardwired "*Timestamp*" with the synchronization of all electronic components that intervene in the data acquisition.
    - Individual access control for all users.
    - Personalized reports and alarm management.
    - Preventive and Corrective maintenance.

- **Class B. Cost-efficient:**
    - Industrial computers, PLCs and other electronic components may include two power supplies connected to the UPS improving the availability and making the maintenance easier.
    - Double network connection with remote booting and no hard disks when possible.

[249] UPS: Uninterrupted Power Supply
[250] Minimum time to recover once the electron beam is down is in the order of one hour in most cases, given the time needed to re-check critical subsystems after a failure and prior to injection. The injection itself is always subject to optimization but a common figure is a minimum of 20 minutes.
[251] Non-critical failures do not stop the accelerator. For example, a diagnostic CCD camera can fail and the accelerator can continue working. The same thing happens with a large number of temperatures, diagnostics, etc.

- Generic “*Timestamp*” for all data acquired.
    - Historical databases with archiving frequencies of seconds, timestamps with precision of milliseconds and one year available for on-line queries.
    - Configurable alarms rules, thresholds and persistent attributes.

- **Class C: Economic:**
    - Single power supply to simplify cabling save costs.
    - One single network connection.
    - Data archiving in the order of 30 seconds or more.

6.2.2.5.1 Availability objectives

Non-critical systems can accept availabilities of about 95%. These do not provoke a loss of the beam and can be repaired not immediately but in working hours in the following days. Critical systems in Synchrotrons require an availability of about 99%, meaning that only 1% of the beam time can be lost due the control system. These requirements are given by the standards in the international community in similar installations. Metrics are maintained in different platforms, such as the service desk portal and the logbooks.

6.2.2.5.2 Objectives after major changes

Service requests, request for changes or any major actuation shall go to the change management committee for approval (plan and budget). Standard changes are executed without this formal step, as they are pre-approved.
Changes affect the service and the service levels agreements must be revised in case of a major change. This is not the case for standard changes, which are assumed to not affect the service.

6.2.2.5.3 Objectives to restore the service after a failure

Configuring service level agreements for control systems is challenging. The response time can be configured in terms of team management, or in other words, the availability of the on-call persons at a given moment. The resolution time depends on the failure and has a different severity depending on whether the service is down or not.
Class A systems services are usually **24x7** and require a **response time** typically **of 1 hour**, since the incident is notified until the support team gets in contact with the user. The resolution time needs to be quick, although in some cases, given that these systems are configured in high availability and fault tolerance, if the service is not down the resolution time can be longer.
Class B systems can be defined as **24x6** with a response time of **1 hour**. The resolution time needs to be quick as well if the service is down.
Class C systems can be defined as **16x7** but with support available only between 7:00 and 23:00 and with a response time of **1 hour** as well.

The resolution time depends on the failure and the effort directly depends on whether the beam is down. Since there is a general annual objective on the beam availability, one strategy is not assigning a resolution time per intervention but considering only the aggregate. If the time is defined, it will rather depend on the subsystem affected.

6.2.3 Control and data acquisition system of an experimental station

This is the general service for Beamlines and experimental stations control systems. The counterpart of the service for the particle accelerators, this includes hardware and software for the data acquisition, human machine interfaces and support for all subsystems.

6.2.3.1 Description

The specific IT service for Beamlines and experimental stations includes subsystems common to the particle accelerators and uses most general IT services as well. In addition, it provides specific software and hardware to carry out experiments at the Beamlines. These may be very specific for each particular Beamline, such as detectors and sample environments.

6.2.3.2 Characteristics

An experimental station needs to control standard infrastructure like vacuum systems, diagnostics, fluorescence screens, digitalization of electrical currents and voltages, motor controllers, and ultimately it is required to provide a robust and flexible interface for the data acquisition. Beamlines use movable elements driven by motors instead of magnets driven by power supplies. The data acquisition paradigm is based on scans.

The control system function is to provide the hardware and software tools to the scientists for the preparation and alignment of the Beamline and the data collection. It includes the appropriate human machine interfaces to configure the instrumentation to synchronize any subset of axes with the combination of detectors required.

Again, the alternative of not doing the control system is not an option. Eventually one alternative could be not to deliver the service as such, but leave the implementation and operation to different groups and visiting scientists, with the consequent impact in the maintenance and operational costs. The service guarantees the level of standardization, simplifying the maintenance of both hardware and software, and making the learning curve easier.

The scope of the service again depends on the strategy of the installation together with multiple external factors.

6.2.3.3 Includes

The same as in the case of the accelerators, this includes the integration of detectors, motors, synchronization, online processing etc. Beamlines and experimental stations rely on the data acquisition software and the instrumentation involved in the experiment, such as diffractometers and sample environments.

6.2.3.4 Excludes

As in the case of the accelerators, the control system service for Beamlines and experimental stations does not include cooling, air conditioning, electrical power distribution or other conventional infrastructures. In some cases, it may exclude as well most data analysis procedures, tightly associated to the on-going experiment. This paradigm is currently changing with the high level of automation of certain experiments and the open access data policies that will derive in providing infrastructure for data analysis on premises.

6.2.3.5 Service level

Several service levels can be foreseen depending on the strategy of the facility. Similarly to the case of particle accelerators (6.2.2.5) the classification in Class A, B or C can also be applied, although sometimes providing less redundancy because of the impact (a failure in the accelerator affects all Beamlines whereas a failure in a Beamline only affects that Beamline).

6.2.3.5.1 Availability objectives

In the case of the Beamlines, it is more difficult to define goals for the availability. The control system is often continuously changing, introducing new functionalities, adding support for new instrumentation etc. The service is stablished normally as a 16x6 basis although it can also be 24x7. The availability is expected to be in the order of 95% (C class), but it is difficult to anticipate to measure, assign and report.

6.2.3.5.2 Implementation of changes and new functionalities

Standard changes should not affect the service level, but in the case of the Beamlines given the fact that the experiments are very diverse and by definition innovative, the configuration, instrumentation, synchronization, sample environment and even motors and detectors can change from one experiment to another. These changes, that many times are considered as standard, can indeed affect the service level as they are performed in short times (few hours) with little testing.

6.2.3.5.3 Objectives to restore the service after a failure

The objectives are often assimilated to Class C 16x6 (7:00 to 23:00), but occasionally they are more restrictive reaching the level of the particle accelerators (see 6.2.2.5.3).

6.2.4 Support services

The support services are needed by the control and data acquisition system but not only. These support services include: communications and networks, archiving and backup, equipment databases, timing and synchronization systems, motor control hardware and software, vacuum, diagnostics, etc. Having a corporate equipment database [6:7] that is used for the installation and maintenance of all accelerators and Beamlines is a key asset in the process.

6.2.5 Incident management

One of the main processes of the service operation as defined in ITIL is the incident management. It shall be centralized, keeping a single point of contact (SPOC) as long as it is possible, and rely on the pertinent tools. These include a service desk built on tools such as JIRA[252], Redmine[253], Request Tracker[254] etc. The portal shall manage the incidents declared by the users, as well as other ITIL operation sibling processes such as problem management, request for changes or service requests. The service desk, shall react on these issues, categorizing and resolving or dispatching them to the appropriate queues or support groups.
Not all incidents are declared on the service desk. Other monitors and alert managers such as *nagios*[255], *icinga*[256], splunk[257], SCOM[258], control system alarm handlers [6:8], on-call text messages alerts or telephone calls can create issues. These issues are first categorized (incidents, problems, request for changes or service request) and registered in the service desk portal to be resolved or assigned to the appropriate queue or person. In some cases, tickets classified as a problem or a request for change may require specific authorization and the creation of a Project to give the appropriate solution. Projects need to be managed following different workflows that will be explained in the next paragraphs.

6.3 Request for change, service requests and project management.

One significant part of services turns into operation when the facility does so. However, services are not static and require maintenance and continuous improvement. The development of new features, the extension of services and the implementation of major changes are formalized by projects. PRINCE2 defines a project as a temporal organization created to deliver one or more products according to the specifications considered in the business case.

---

[252] JIRA: Jira is a software developed for service and project management developed by ATLASSIAN. https://www.atlassian.com/software/jira
[253] Redmine: Service and project management free and open source software tool written in Rubi on rails (GPL license) with wide support for relational databases (for example MySQL): http://www.redmine.org
[254] Request Tracker (RT): Service management free and open source software tool developed in Perl and distributed under a GPL license. GPL: http://bestpractical.squarespace.com/request-tracker
[255] Nagios: is a tool to monitor and manage the alerts in computers, network switches and in general any computing infrastructure. Is distributed as Free and Open Source Software under a GPL license.
https://www.nagios.org
[256] Icinga: It is derived from Nagios and also distributed under GPL: https://www.icinga.com
[257] SPlunk. https://en.wikipedia.org/wiki/Splunk
[258] Microsoft SCOM System Center Operations Manager.
https://en.wikipedia.org/wiki/System_Center_Operations_Manager

PMBOK[259] defines a project as a planning consisting in a set of activities coordinated and interrelated.

Any facility or scientific installation executes projects although may be formalized differently and with various levels of detail. During the installation phase, the coordination of tasks such as civil works, installation of instrumentation and commissioning of each part is a critical success factor [6:9]. They typically involve tens of call for tenders with different suppliers. Unlike services, projects are limited in time. They have a beginning and an end with a schedule and resources associated. The whole installation process can be considered as a project with a detailed schedule, milestones, resources and interrelations between products, stages and tasks, and very important, the detailed acceptance criteria for the products and the whole project. This principal project in most cases breaks down in smaller projects managed by different boards coordinated from a single master plan.
Turning the facility into operation involves logically more effort on the delivery of the services and a reduction in the number of projects. However, there is always a continuous service improvement and other major changes and requests requiring projects.

6.4 PMBOK, PRINCE2 and Scrum

PMBOK describes a collection of good practices oriented to project management and the breakdown in tasks and specific concepts, such as communication, risks, budget, schedule and others. The project manager has a principal role that needs to make decisions. It describes particular techniques and goes down to the details of management and execution. Although sometimes presented as competitors, PMBOK and PRINCE2 can be considered as well as complementary, since PMBOK is a standard more oriented to general principles and concepts and PRINCE2 is a methodology focusing on processes and roles. PMBOK is more extended around the world although PRINCE2 is more popular in Europe. In particular, facilities such as ALBA, but also ITER and the ESRF have incorporated to some extent PRINCE2 themes and principles to their project management.

Opposite to PMBOK, PRINCE2 focuses on what to do more than on how to do it. PRINCE2 was created by the British Office of Government Commerce (OGC) and oriented to IT projects. It is based on a set of processes and themes and covers the whole lifecycle of the project. It also defines the roles of the project manager, project board and the Executive as the ultimate responsible for the decision-making. Other fundamental roles are the Senior User, and the Senior Suppliers both also part of the project board together with the Project Manager and the Executive. Team leaders and quality assurance are other roles present in every project.

[259]PMBOK: Project Management Body Of Knowledge: Guides, terminology and standards for project management. PMI. Project Management Institute. Non-Governmental Organization for project management.

PRINCE2 is based on seven principles to be assured by all projects, seven themes or aspects to be managed in all projects and seven processes that define sequences and activities [6:6]. Scrum is an agile project management methodology, which unlike traditional software engineering models like waterfall, prioritizes incremental development and the continuous interaction with the customer. In fact, the customer participates in the project and has an empiric control because is being continuously informed about the partial outcomes, notably at the end of each sprint, and so he can validate them and take the appropriate decisions about the priority and definition of the next scheduled tasks. Teams are self-organized and have a close and continuous interaction with each other, with daily fifteen minutes standup meetings as well as with the clients. At the beginning and at the end of the sprints the team has planning and retrospective meetings. The team auto-evaluates their velocity and overall performance to be considered for further sprints.

6.5 PRINCE2 projects in a scientific installation

When a project starts, a mandate with the name and description of the project is created to evaluate its feasibility. Afterwards the project enters in the pre-project stage, where the project boards and the roles are defined. The project manager creates a project brief, a draft that includes the preliminary version of the business case[260] compiling the motivations and the reasons to carry out the project, the stakeholders, benefits, risks and restrictions. The project brief describes also the products and proposes an approach analyzing the possible alternatives. Once the board approves the project brief, the project enters into the initiation phase where the project manager gathers all relevant and required information in the Project Initiation Document (PID[261]), describing goals, detailed acceptance criteria, quality assurance strategies, risk management, communication management, components, products, stages, milestones and the overall plan. This is a key stage to determine whether the project has to be actually launched or discarded. In scientific facilities such as synchrotrons, a project can be a large endeavor described in the strategic plan such as installation of a new Beamline, where the business options are reduced to the different project approaches and never considers the "not executing the project" option, as it has been previously approved by higher decision making councils. It can also be a project more internal to the operation of the facility, such as for example implementing a new service desk portal with new features, where the board decides whether to execute the project at all as well as the different business options. The communication management, includes regular highlight reports, exception reports when the project has significantly deviated from the plan and requires a decision by the board, end of stage and

[260] Business Case: It is one of the themes of PRINCE2 and a document used to determine if the project is and continues being viable and appropriated. In other words, it answers the question whether the investment is still justified according to the strategy and standards of the organization.
[261] PID: In PRINCE2 terminology: Project Initiation Document.

project closure reports, with an executive summary with the accomplished (or not accomplished) goals, the overall performance of the teams and the lessons learned.

6.6 Management tools

PRINCE2 defines processes, themes and principles and does not go to details on the tools. A project produces a considerable amount of information managed mostly by the project manager. A management tool reduces the workload, speeds up the process, improves the communication with stakeholders and team members and gathers the information in a central repository, not only of the ongoing projects but also of the ones completed and closed.
Establishing software tools to manage the project processes, documentation, communications and resources is a critical success factor to effectively follow up and manage the workload and effort. Combining these data with the time spent in services, tracks down the total costs imputed to the different customers and clients. ALBA has established these type of tools, first as applications in the intranet, such as CPM and TimeDB [6:10][262], combined with issue trackers such as Redmine and later migrated to Attlassian JIRA software and service desk platforms[6:11][6:12], the state of the art and one of the market leaders.

Time management is a recurrent problem in every organization. Learning from experience and from previous errors requires crosschecking estimated efforts with logged (real) efforts in projects and services. A database of time and efforts dedicated to each task is crucial to evaluate the real cost of a project or a service and after all to determine if the resources of an organization are properly used and aligned with the strategy.

TimeDB Provides a repository, and web human machine interface where members can visualize their entire time registry to different projects and services and can as well register additional time devoted to other tasks. Data is stored in a MySQL relational database but could be any other SQL database. These data are a strategic asset to report on the time assigned to a particular project, service, subsystem, or customer, and enable managers to take the appropriate decisions.

[262] CPM (Computing Project Management) and TimeDB (Working time database) are tools developed and managed by the MIS group (Management Information Systems) in the Computing division at ALBA.

6.7 PRINCE2 and Scrum

There is much controversy around combining PRINCE2 and Scrum[263] [6:9]. Hereafter I describe the initiative and successful experience managing PRINCE2 and Scrum projects at ALBA since 2013. Other institutes like ITER have also undertaken similar initiatives. One of the principles of PRINCE2 is the adaptation to the environment[264], so if the project is Agile, PRINCE2 will adapt to the project environment. Certain equivalence can be actually made between PRINCE2 and Scrum roles as described in Figure 6-2. However, this is not a perfect one to one match. They have a different scope with important nuances. For example, a scrum master (leading high-level consultancy) is not the same thing as project manager (assigning and distributing the tasks) and assigning the two roles to the same person may create conflicts and perturbations.

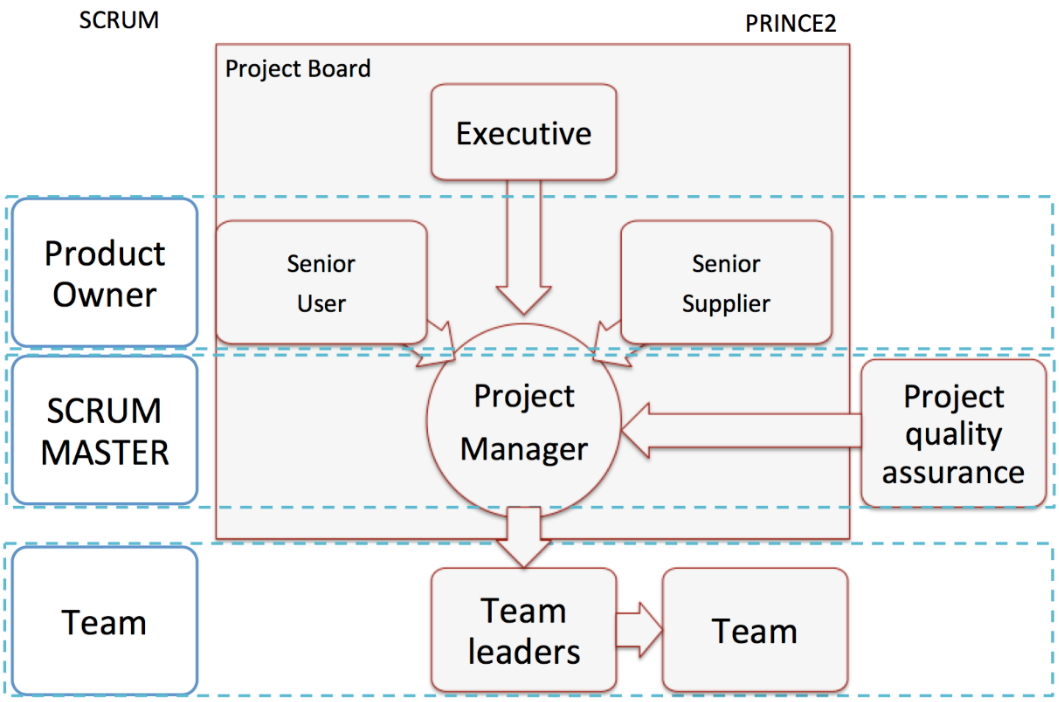


Figure 6-2: Correspondence between Scrum and PRINCE2.

A project needs an overall plan to state whether is viable and aligns with the overall strategy. Based on this plan, once it is approved it gets the resources for the execution. PRINCE2 is well adapted to define a formal structure for the organization to evaluate the needed goals and resources and regularly monitor the evolution. The PRINCE2 project board represents the

---

[263] Available on internet are many pages and discussions with different opinions and a lot of controversy. There are a number of success stories (for example: https://www.scrumalliance.org/community/articles/2014/march/success-story-prince2-scrum-delivers-ontrak-on-tim) that highlight the benefits of their use together.

[264] "Tailored" to the project environment, size and resources [[6:6]].

interests of the organization and the user, makes the relevant decisions such as change priorities, devote more resources or even abort the project. Scrum, on the other hand, offers the appropriate tools to efficiently manage the day-to-day work. An agile environment does not mean chaotic.

The approach adopted at ALBA follows this reasoning with a slightly different chronology. The Computing Division at ALBA adopted the PRINCE2 methodology in 2009, later extended to other departments in the organization. In 2013 the software groups of the division adopted Scrum for the management of the teams and tasks. Scrum was adapted first to the existing PRINCE2 processes[265] while PRINCE2 needed to be tailored accordingly. Scrum adapts well to key PRINCE2 processes, in particular product deliver management. Scrum sprints could be mapped to PRINCE2 stages, although this is not always the optimum. The velocity and the work done during sprints varies depending on the availability of the team members and the service management tasks that can be running in parallel.
More precisely, an equivalence could be established between Scrum and the seven principles of PRINCE2:

1. Business justification at any time:
    - The Scrum *backlog*[266] is always monitored to adjust the priorities.
2. Learning from experience:
    - Scrum establishes retrospective meetings at the end of each sprint.
3. Definition of roles and responsibilities[267]:
    - Scrum defines its own roles: *Scrum Master*, *Product Owner*, *Team*, that differ from PRINCE2´. However, there is to some extent a certain equivalence as shown in Figure 6-2.
4. Management by stage.
    - Scrum sprints could be mapped to stages. In some scenarios, releases could also be mapped to stages.
5. Manage by exception. When time, cost, quality, risks, or other tolerances are exceeded, the project manager proposes an exception for the board to consider and eventually approve.
    - Scrum´s product backlog can be modified at any moment to undertake any exception in close collaboration with the product owner, scrum master and the team. **PRINCE2** only brings a **formal approval** step that is needed to ensure

[265] Some Scrum experts' argument that Scrum cannot be partly followed and when combining it with PRINCE2, it loses its nature (https://www.scrumwithstyle.com/prince2-agile-victim-agile-pt1). In this chapter another point of view is shown with practical implementations of projects managed with PRINCE2 in particular related to resources change management and decision-making and at the same time combined with SCRUM for managing the day to day teamwork.
[266] The list of tasks and description from which the candidates to be part of the next sprint are selected.
[267] PRINCE2 defines its own roles: Executive, Project Manager, Senior User, Senior Suppliers.

that the project with this exception still aligns with the overall strategy, or simply that the required resources can be allocated.

6. Manage products. Acceptance criteria for the different products are agreed and clearly defined from the beginning.
    - Scrum´s sprint backlog gathers all the scheduled tasks after agreeing with the product owner the quality and acceptance criteria.
7. Tailored. Scrum is as well adapted to the environment. Short sprints with reviews and retrospectives allow a closed loop adjusting many parameters like velocity of the team, priorities of different products, etc.

PRINCE2 defines seven themes as the pillars of the methodology:

1. Business Case: Refers to the justification of the projects and alignment with the strategy.
    - Scrum's Product Owner assumes the role of defining priorities of tasks to take part in the sprint backlog[268]. This alignment with the strategy at a lower level enhances and complements well the business case, taken as a master.
2. Organization: Defines the organization of the project with roles and responsibilities.
    - Scrum defines its own structure, quite simplified compared to PRINCE2. However, there are suitable equivalences for the use of both together (Figure 6-2). The Product Owner is assimilated to the Senior User, as in charge of defining requirements and prioritizing tasks. Sometimes the equivalence can be with PRINCE2's project manager or senior supplier, more in particular when the Scrum organization is encapsulated in PRINCE2's product delivery management and is seen as a black box from the container PRINCE2 project. The Scrum Master can be assimilated to PRINCE2's project manager or team manager in some cases.

3. Quality: Both PRINCE2 and Scrum focus on quality although in different (and complementary) ways. PRINCE2 continuously assures that the project is progressing according to the business case and the plan. Scrum focuses more on "hands on" quality, with for example automated unit tests and continuous integration in software project with continuous feedback from sprint reviews.
4. Plan. This answer the questions of how long it will take and how much it will cost.
    - This theme is considered fundamental in both PRINCE2 and Scrum, but approached differently. PRINCE2 establishes plans breaking down the project in products and stages. This task is assumed by the project manager in collaboration by the senior user and supplier and approved by the board. Scrum

[268] Sprint Backlog: This is the list of tasks with their weight that can be selected for a sprint, taking into account the team speed and the duration of the sprint.

establishes plans based in the capacity and velocity of the teams, and the product owner is responsible for managing the sprints and deliveries.

5. Risk. PRINCE2 identifies risks upfront with severities and probabilities proposing mitigation plans. Scrum also manages risks although the mitigation of these is somehow considered as another task in the backlog.
6. Changes. The theme defines how to proceed in the case of major changes in the specification. PRINCE2 states that changes must be communicated by an exception report and approved by the project board (excluding the standard changes that are by definition pre-approved). Scrum assumes that changes can happen at any moment (agile) and are integrated in the same or in the following sprints. The combination of both methodologies brings value since Scrum provides flexibility in the every-day situations and PRINCE2 ensures the consistency of these changes with the strategy.
7. Progress. "Continuous improvement" monitors and answers how the project is going. Scrum retrospectives match to some extent PRINCE2's lessons learned in highlight or of stage reports.

6.7.1 Implementation

Introducing Scrum in a PRINCE2 environment needs reviewing the seven PRINCE2 processes to adapt them to Scrum methodologies when applicable [6:13].

1. Starting up a Project. The project draft with a preliminary business case and a first project approach is created in this phase. This project approach explains the use of Scrum for team and delivery management. The approach shall be explained to the board and in particular the senior supplier who must interact regularly with the Scrum teams and constantly review priorities and requirements.
    - Scrum's product owners and Scrum master roles are defined here as well.
2. Directing a Project. This PRINCE2 process does not involve a particular Scrum counterpart. It relates to a number of activities and responsibilities of the project board such as approving the delivery of the project, the initiation of each stage, etc.
3. Initiating a Project. The PRINCE2 project manager creates the Project Initiation document. The goal of this process is to establish a solid basement for the project with a clear alignment with the strategy of the organization The project manager shall define and document strategies for configuration, risk and communication management, quality assurance, plan, stages and tolerances. This process could include a Scrum kick off meeting.
4. Controlling a stage: This process keeps the focus on the deliveries and assesses that risks are under control. The project manager produces highlight reports according to the communication plan. Scrum teams keep the product backlog updated, having regular meetings with the product owner at the end of each sprint and interacting with PRINCE2's project manager.

5. Managing Product Delivery. This process can be fully assimilated by Scrum, where the teams manage the sprint backlogs associated with the backlog of the project.
6. Managing Stage Boundary. PRINCE2 methodology establishes that the project board needs to approve the closure of a stage and the initiation of the next one, done after a report prepared by the project manager. Scrum's sprint reviews and retrospectives are the counterparts. Scrum reviews the backlog and plans for the next sprint and PRINCE2 complementary reviews the backlog and the plan to ensure that the overall progress and goals are still justified.
7. Closing a Project. This process compiles all documentation to close the project analyzing the results the progress and the lessons learned. Scrum retrospectives are inputs to this process.

6.8 Time management and workload of the different teams

As discussed in the previous paragraphs the members of the teams often assume development, service management and maintenance tasks in parallel. Multidisciplinary teams have certainly many advantages, notably the widespread knowledge, but sharing persons between projects and services entails an extra complexity. Having members in project teams that also manage services and deal with clients and customers is intrinsically difficult to manage, adding complexity to the creation of plans, the coordination and the precise allocation of labor hours.

The sprints defined in projects should be respected as far as possible, but incidents and corrective maintenance activities in general tend to be difficult to anticipate and can take higher priority. The continuous improvement process shall encompass this difficulty and dispose data on the performance, incidents, and unforeseen events in general in order to correctly adjust the plans for further cycles. Service and project management tools allow to register working time related to tasks and issues. Gathering all these sources of data in a central point is critical for readjusting processes and plans. The adoption of these tools and best practices at the early stages during the constitution of the teams is an important factor for the "team building". Figure 6-3 shows a snapshot of the time registry application (timeDB) with the initial python-Qt interface (2005-2009) and the evolution to web technologies (Plone, 2010-2017) [6:10].

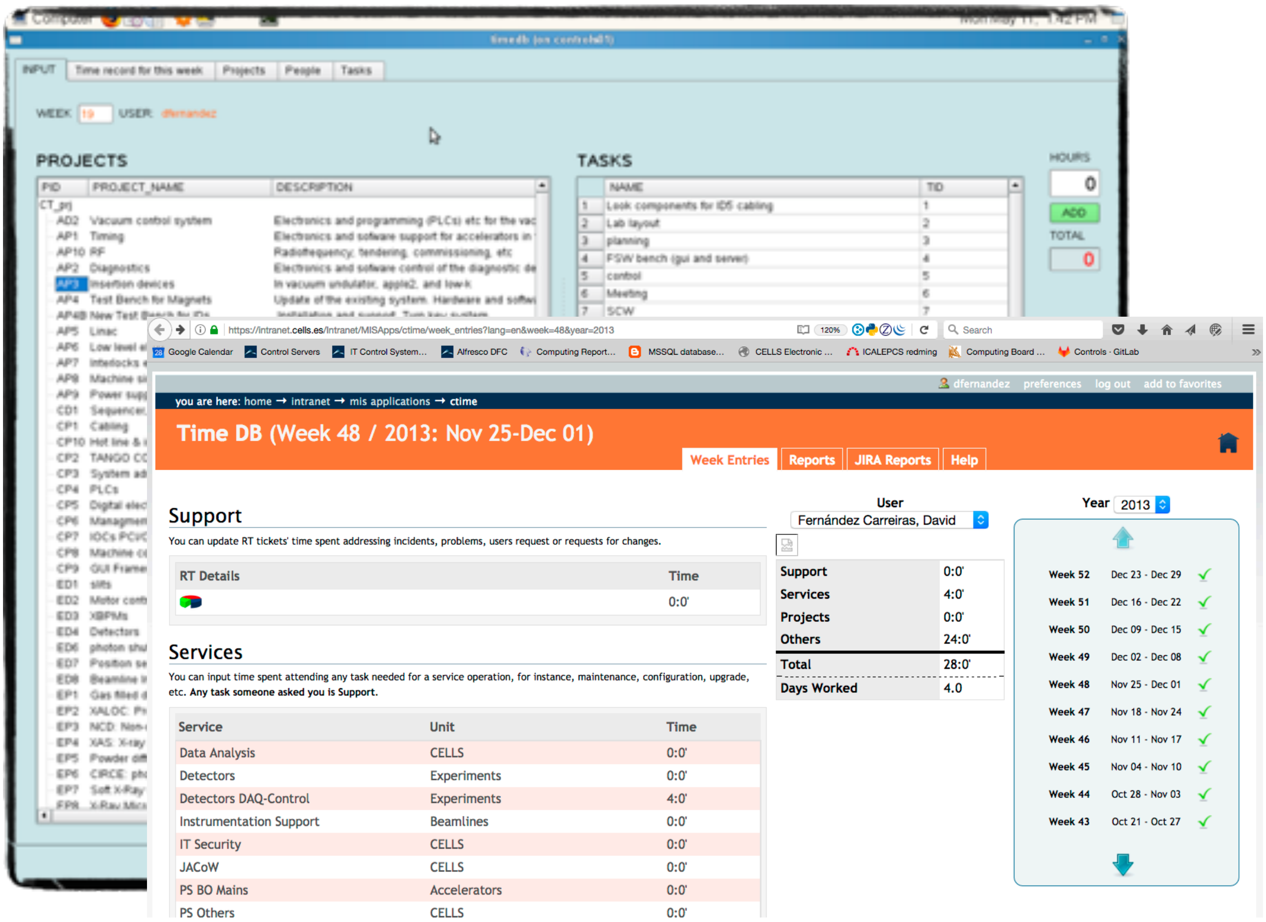


Figure 6-3: View of the evolution of the human machine interfaces and functionalities of the time management application (timeDB – ctime (MIS-ALBA)).

6.9 Summary

The maintenance phase must be planned at the beginning of the project. The construction phase takes a huge amount of resources and generates peak loads that may result in an under-dedication or underestimation of maintenance and service provision costs and workload. This relates to the tools to manage the instruments, the spare parts and the maintenance activities either corrective or preventive as well as the tools that manage labor, projects and services. Project and service management formal approaches are critical success factors for the cost-efficiency of the whole institute. They shall be in place from the early stages of the project, to adopt methodologies and standards in both instrumentation and software development but also in service and project management. Formal project management methodologies such as PRINCE2 combine well with agile methodologies such as Scrum for software development (but not only; electronic designs could also be managed by Scrum). Scrum brings the project execution closer to the client and makes an incremental design possible with a sort of continuous monitoring of the products, the alignment with the purpose and a continuous refinement of the requirements. PRINCE2 provides a more formal approach and helps to keep the goals of the projects, schedule, workload and costs aligned with the overall strategy. When projects are carried out in parallel they compete for resources, in particular manpower. Therefore it is crucial to have the appropriate tools to manage that the execution follows the foreseen plan and to document the deviations, overall costs and impact of projects per customer and unit. These processes shall provide the relevant information to the project board for the approval workflows.

The adoption of ITIL best practices for service management enables the follow-up, optimization and the continuous service improvement of the services. This is particularly important for managing teams where members assume tasks in projects and service support in parallel. The correct tailoring of ITIL and project management processes according to the size of the projects/services and teams is a critical success factor for preventing too much paperwork overcoming the desired agility.

Agile projects and services improve the user satisfaction because they adapt better to the continuous changes in the requirements so common in scientific environments. Both projects and services continuous improvement processes require a constant monitoring of the outcome and performance.

6.10 References

[6:1] "Maintainability Design Handbook for Designers of Shipboard Electronic Equipment", NAVSHIPS 94324, Washington, D.C., U.S. Department of the Navy, Naval Ship Systems Command, 1964.

[6:2] ISO/IEC 15288:2008, Systems and software engineering – System life cycle processes, 2nd Edition, Geneva: International Organization for Standardization, 2008.

[6:3] R. Gulati, "Maintenance and Reliability Best Practices", Industrial Press, New York, 2008.

[6:4] B. S. Blanchard, "Logistics Engineering and Management", 6th ed. Prentice-Hall, Inc. 2003, 5th ed. 1998.

[6:5] "ITIL Service Strategy", "ITIL Service Design", "ITIL Service Transition", "ITIL Continual Service Improvement". Office of Government Commerce (OGC), TSO Ireland, 2011.

[6:6] "Managing Successful Projects with PRINCE2", Office of Government Commerce (OGC), TSO Ireland, 2009.

[6:7] D. Beltran, I. Costa, A. Camps, D. Fernández-Carreiras, J. V. Gigante, J. Klora, O. Matilla, V. Prat. "Alba Control and cabling database". Proceedings of ICALECPS 2009 (p. 423). Kobe, Japan.

[6:8] S. Rubio-Manrique, F. Becheri, D.Fernández-Carreiras, J.Klora, L.Krause, A. Milán-Otero, Z. Reszela, P. Skorek. "Extending the alarm handling in Tango". Proceedings ICALEPCS 2011 (p. 63). Grenoble, France.

[6:9] "PRINCE2 Agile". Axelos, PPM official publisher.

[6:10] D. Fernández-Carreiras, F. Becheri, S. Blanch, A. Camps, T. Coutinho, G. Cuní, J. Gigante, J. Klora, J. Lidón, O. Matilla, J. Metge, A. Milán, J. Moldes, R. Montaño, M. Niegowski, C. Pascual-Izarra, S. Pusó, J. Jamroz, Z. Reszela, A. Rubio, S. Rubio-Manrique, A. Ruz. "The commissioning of the control system of the accelerators and Beamlines at the Alba Synchrotron". Proceedings ICALEPCS 2011 (p. 432). Grenoble, France.

[6:11] D. Fernández-Carreiras, G. Cuni, J. Klora, M. Martin, O. Matilla, A. Nardella, A. Pérez, V. Prat [on leave], D. Salvat , Alba-CELLS, Barcelona, Spain. "Using Prince2 and ITIL practices for computing project and service management in a scientific installation". Proceedings of ICALEPCS 2013 (p. 517), San Francisco, USA.

[6:12] M. Martin, A. Burgos, C. Colldelram, G. Cuni, D. Fernández-Carreiras, E. Fraga, G. García López, O. Matilla, A. Pérez-Font, D. Salvat. "Streamlining support and development activities across the distinct support groups of the Alba synchrotron with the implementation of a new service management system", Proceedings of ICALEPCS 2017, (p. 298), doi:10.18429/JACoW-ICALEPCS2017-TUMPL02, Barcelona, Spain.

[6:13] G. Cuní, F. Becheri, D. Fernández-Carreiras, Z. Reszela, S. Rubio-Manrique. "Introducing the SCRUM framework as part of the product development strategy for the ALBA control system". Proceedings of ICALEPCS 2015 (p. 60) Melbourne, Australia.

[6:14] K. S. Rubin, "Essential Scrum. A practical guide to the most popular Agile process", Addison-Wesley, 2012.

7 CYBER-SECURITY AND CONTROL SYSTEMS

Since the nineties with the democratization of personal computers, and in particular with the apparition of Microsoft Windows operating systems, the cyber-security (security hereafter) is a discipline that is continuously gaining attention. Security means not only software such as antivirus or firewalls, but also control policies, infrastructures such as authentication and authorization systems, certificates, and in general all mechanisms in place for preventing unauthorized access, in other words, managing identities and permissions to read, write or remove any piece of information. It is in fact a wide discipline including a continuous update and training of the users and stakeholders.

Control systems and more in particular industrial control systems have not been much concerned about security. This was the case because they did not need it. Systems were usually isolated both physically and from Internet. A reduced number of people had access to them and they were not frequently upgraded. This is no longer the case. Control and automation systems both applied to industrial factories or scientific installations are connected to the corporate networks, have access to the Enterprise Resource Planning systems (ERPs), databases, stocks, bills of materials, etc. and of course they are often somehow connected to internet, although properly protected with the appropriate firewalls, proxies, virtual LANs, etc.
Key performance indicators and metrics of IT services, as well as newspaper coverage and the number of court cases show that cybercrime is raising together with the number of users of internet. Countermeasures are undoubtedly in progress, but so it is the sophistication of the attacks[269].

7.1 Programmable Logic Controllers

In 2010, the cyber-security in the field of control systems experienced a major event. Stuxnet, an iworm[270] affecting Windows systems and able to read-write in Siemens PLC systems hiding the changes was detected by a Byelorussian company in Uranium treatment plants in Iran. This is the first reported video that is able to reprogram and spy PLC and industrial SCADA system with potential catastrophic consequences for any factory. The case of Stuxnet looks proven to be orchestrated by Mossad [7:1]. It was designed to infect PCs with Siemens diagnosis and configuration software STEP7/WinCC, take control of a variable frequency drives present in Uranium treatment plants in Iran, and cause permanent damage to those devices. It infected a

[269] The page www.cybercrime.gov shows court cases related to cybercrime in a wide domain, affecting computers, networks and cell phones.
[270] Computer worm: Self replicated software that expands autonomously on the network.

hundred thousand PCs of which 60% were in Iran, 10% in Indonesia and the rest in other parts of the world[271].

Stuxnet is the groundbreaking event to focus on industrial control systems cyber-security [7:2]. Factories are in a way connected to internet and therefore under a risk without requiring physical access to the factory. Modern systems interconnect SCADAs that control the factories with other systems such as ERP, with corporate databases, bills of materials, business intelligence, etc. In fact, SCADAS, tend to scale out managing stocks, maintenance works, budgets amongst others. On their side, ERPs integrate competences before assumed by SCADAs. More importantly, big data infrastructure, machine learning techniques and business intelligence software complete the circle to offer the relevant information in the adequate format for a continuous service and manufacturing improvement. In any case, these achievements require PLCs to be reached from the corporate networks, and therefore from internet with the consequent risks. The cyber-security must consider these facts, take the initiative and must be an initial requirement for all new projects.

7.2 Network design

Scientific installations control systems share many requirements with industry. They used to be designed ad-hoc from scratch, but the paradigm has changed and today they extensively use standards from industry such as PLCs, industrial computers and databases. On the other hand, industrial systems used to be designed around PLCs and isolated from the outside world, nowadays, in 2019, industrial systems still use PLCs extensively, but combined with other technologies like industrial computers, different kinds of databases –including open source products- for stock management, maintenance, recipes, etc. and other corporate applications such as ERPs. Industrial systems are today broadly connected to the outside world, making them more powerful, but at the same time much more vulnerable to cybercrime.

Figure 7-1 shows and example diagram of network topology for a synchrotron-like installation. Data networks are separated by firewalls. The design goal is offering services to users, in terms of for example remote access to Beamlines for remote control of an experiment, or access to data, results and data analysis programs and infrastructure.

Scientific installations profit from the concept of federation of networks. The ALBA synchrotron, for example is connected to “Anella científica” from the “Consorci de Serveis Universitaris de Catalunya” (CSUC) using fiber optics symmetric 500Mbps/1Gbps connections (2019). These networks are integrated in the Research network of Spain (Rediris),

---

[271] Sutxnet was designed to infect PLCs in uranium treatment plants in Iran. It was introduced very probably in a USB drive inside the factory because PLCs were actually not physically connected to internet. It replaces S7 windows shared libraries (.dll) and can alter process variables for displaying or historical archives. It is a sort of “man in the middle” between the PLCs and the SCADA (https://en.wikipedia.org/wiki/Stuxnet).

which is part of Géant, a federated network that comprises the main European research networks.
This infrastructure brings value to the research centers and universities providing services and increasing the overall productivity, but at the expenses of a considerable increment of cyber-security requirements.

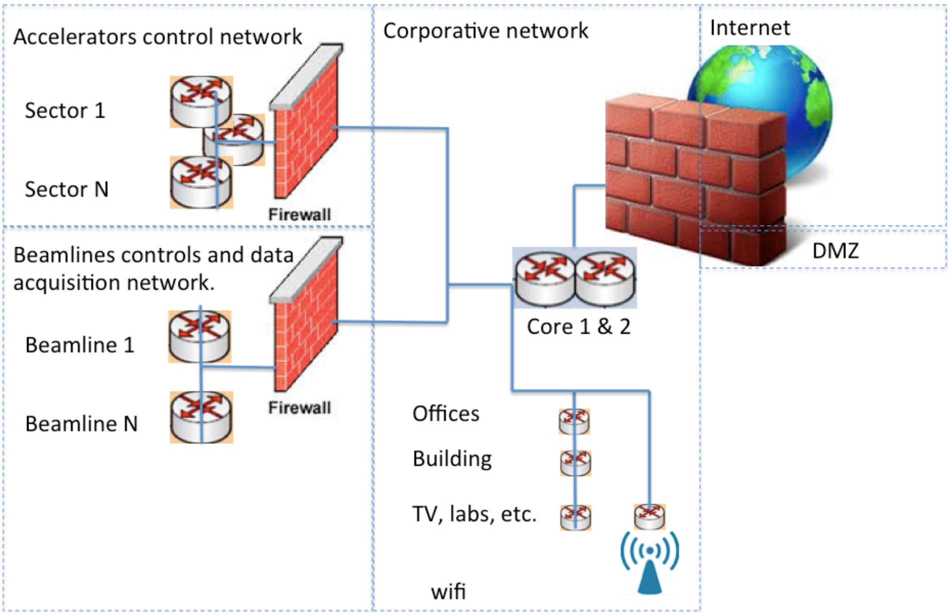


Figure 7-1: Cyber-security from the perspective of network design. Example of a Synchrotron facility.

Physically isolated communication networks are no longer feasible in many cases. When a device is connected to the network, it is exposed and vulnerable. Occasionally in particular in industrial systems they introduce data-diodes, that physically limit the communication to one direction. They bring a high level of security (read-only; impossible to write unless with physical access to the installation) but in some cases this is not operational.
Segmentation is a key paradigm in the design of data networks and firewalls are key players[272]. When services need to be exposed to internet, DeMilitarized Zones (DMZ) are often set up, acting as a security layer between the internet and the intranet.
As aforementioned, control networks are somehow isolated from the corporate network, from intranet and of course from the internet. For example, the so called “technical network” at CERN comprises several tens of different systems of different sizes, segmented with firewalls, with access restricted at the *router* level 1-N ACLs[273]. In the case of a synchrotron facility, Beamlines, machines and corporate networks are separated by firewalls. Some Beamlines can be grouped and accessed with an independent firewall. The segmentation is also achieved by

[272] Firewalls: Devices that act as barriers, filtering protocols and ports, and preventing unauthorized communications between networks.
[273] ACL: *Access Control Lists*

virtual networks (VLAN). In the case of the ALBA synchrotron, each Beamline has independent hardware infrastructure including routers and in some cases dedicated links to the data center, although the firewall is common for all Beamlines. The accelerator networks are also independent with personnel access control and protected by dedicated firewalls, in order to isolate possible attacks from users, visiting scientists, students, etc. Segmenting networks certainly increase the security but may affect the usability. The communication between networks requires the appropriate configuration of gateways, aiming to maximize the security with the minimum affectation to usability. Physically separating networks is even worse, in terms of usability. A good example in this sense is the building control system network at ALBA, which for historical reasons is totally independent and isolated from the corporate network but needs to communicate with the central services in order to manage alarms, merge historical data, plot combined trends and correlate process variables between water cooling circuits and Beamline and accelerators control systems; water temperature, pressures, environmental humidity, etc.

7.2.1 Can the control system network be isolated?

This is a recurrent question. Control systems used to require to be cut off from the outside world. The motivations are among others: (1) be immune to failures of third-party systems not directly related to the control system, (2) security in the sense of being resistant to third-party human errors not directly related to the operation, and (3) cyber-security in the sense of being safe from cyber-crime attacks, all having direct consequences in the operation and experiments. There are particular cases where systems need special requirements. Meaningful examples are personnel safety systems (PSS) for particle accelerators and Beamlines that require the local authorities' approval[274]. Special cases are the Beamlines and experimental stations for medical diagnosis and treatment, like ID17 at the ESRF, that deal with animals and occasionally with human patients with the consequent specific actuations, workflows and approvals. There are particle accelerators dedicated to diagnoses and therapies on human patients, such as the Medaustron[275], a proton synchrotron for cancer treatment in Austria. All are subjected to specific norms, which include certification, validation, audit and approval processes to get and maintain the operation permit. The design paradigms dictate fail-safe configurations, redundancy and diversity, specific installation procedures, such as dedicated cable trays, fieldbuses and network infrastructure [7:3].

In order to answer whether the control network can be isolated, some assumptions must be made, and the final answer will depend on the environment and on the different subsystems. Critical systems such as the PSS as above-mentioned are usually isolated with an independent

[274] In Spain the approval is issued by the CSN (Consejo de Seguridad Nuclear).
[275] http:/www.medaustron.at

infrastructure, where actions on the system are implemented compulsory by physical actuators, the networks and fieldbuses have independent hardware, cables and cable trays and where the non-fail-safe elements, such as the data network are only used read-only for monitoring purposes. But “isolation” does not mean to prevent access from outside which will compromise the usability of the system. Instead, a read-only gateway can gather these read-only values for further archiving, diagnostics purposes, or conditions for user-defined alarms. In this particular case, it is important to note that this infrastructure: gateway, network, etc. can be cut off without in any case compromising the safety (although affecting the diagnostics and monitoring functions).

Particle accelerators and Beamlines for therapeutic and diagnosis purposes are special cases often faced to ad-hoc solutions. Local authorities often require compulsory safety measurements, such as for example making explicit the case of isolating the system from the outside word, which means foreseeing the design of the network according to these rules. These architectures define Tiers. A common approach to this multi-tier control system architecture, defines three. Tier-1 is the presentation layer that offers human machine interfaces, reporting tools, archiving, macro and sequence execution etc. Tier-2 provides the protection system logic, interlocks, process automation and access to hardware. Tier-3 comprises the field sensors and detectors. The corporate data network interconnects Tier-1 and Tier-2 whilst the fieldbuses communicate Tier-2 with Tier-3. Usually, when isolating the control system network infrastructure all Tiers must be kept in the local network, so the services are maintained.

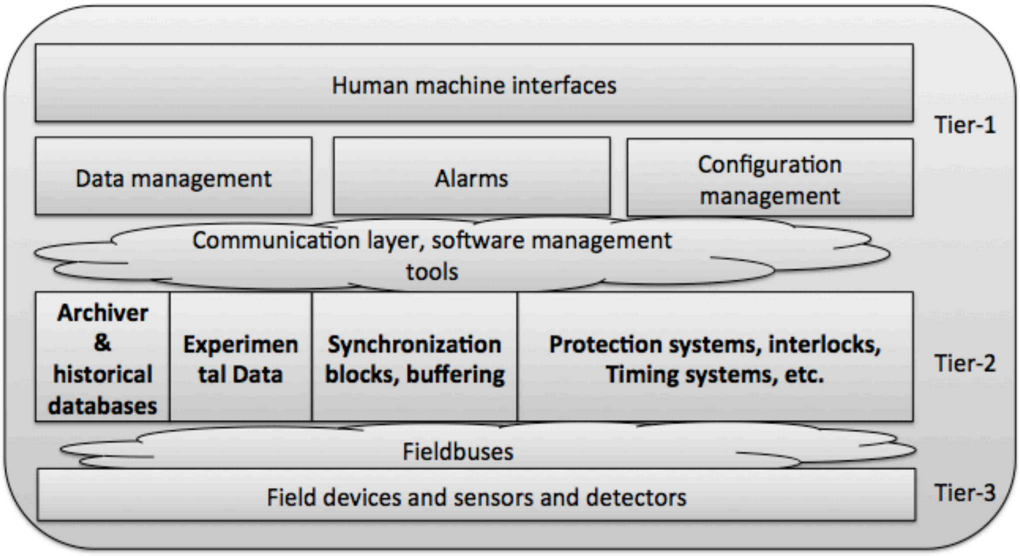


Figure 7-2: 3-Tier architecture block diagram

When a control system is designed to work in an isolated network, which means that it is corporate network fail-safe, shall be periodically audited and tested in order to detect possible failures or unadvertised incompatibilities after eventual modifications or upgrades of the system. The system shall continue working when disconnected from the corporate network and shall be autonomous in the sense that can be started, operated and stopped when disconnected. A control system of an installation is a collection of control subsystems, that although in principle can be cut from the outside network, they may not be able to achieve it in practice because they use often a number of corporate services such as file systems, authentication, domain name services, amongst others. The fact is that a control system is not isolable by default and if an explicit requirement exists, such as for example the medical Beamline at the ESRF or the PSS, the system shall be conceived and designed accordingly, with the appropriate assumptions in terms of duplication of services, extra maintenance costs, and periodic audits.

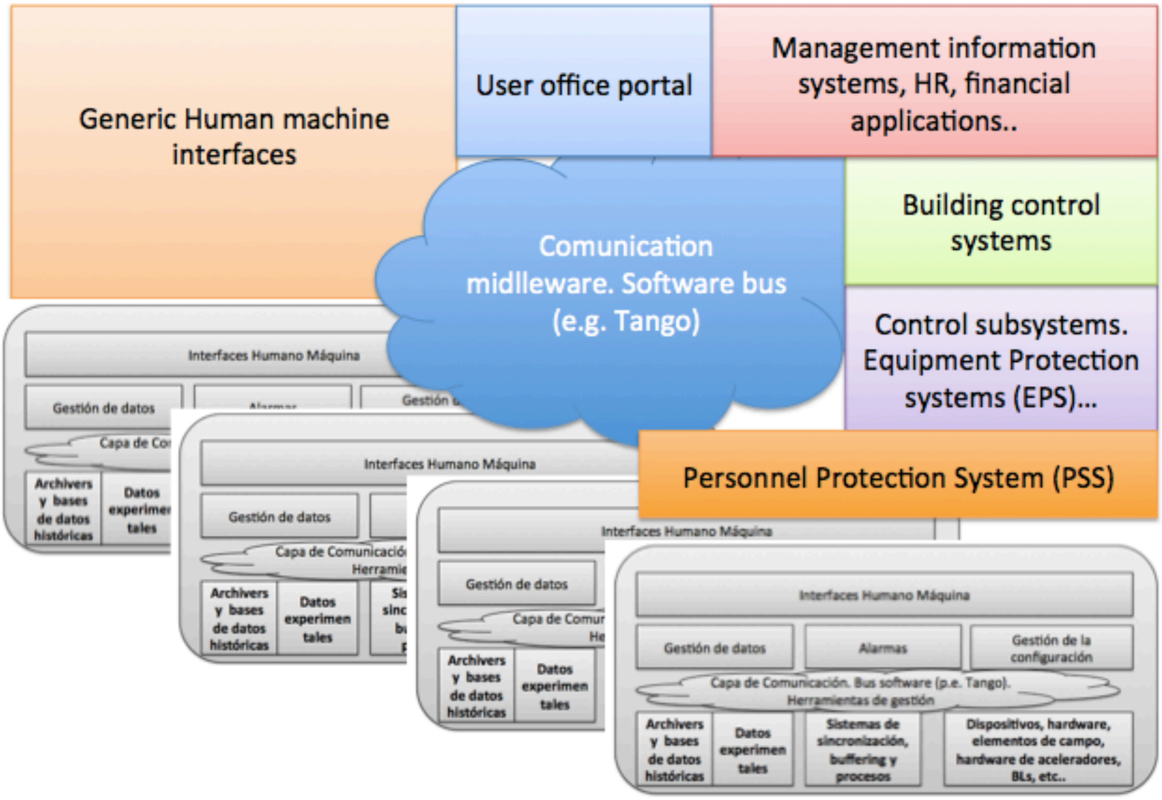


Figure 7-3: The control system of a large facility is a collection of dedicated control systems. This picture shows some of the building blocks. Every Beamline has its own network control system and network infrastructure.

Generally speaking, networks more and more interconnected and are not easy to isolate. For example, at the ALBA synchrotron, every Beamline has an independent control system with a specific Tango infrastructure and central database. However, all Beamlines depend on central network services such as DNS, LDAP, data storage, license servers, databases, etc. They

cannot be isolated, but in fact they do not need to be. Only the PSS due to legal requirements implements a dedicated network infrastructure.
Data networks are so widely used that a critical network failure often requires the particle accelerator to be stopped that is the beam dumped.

On the other hand, requirements are getting more ambitious. The facilities are required to interconnect or at least share certain services and shall share the authentication infrastructure to provide a sort of a federated single sign on. Users should be able to access data across different facilities with their single credentials. They could connect to a particular Beamline carrying on a particular experiment with these same credentials.

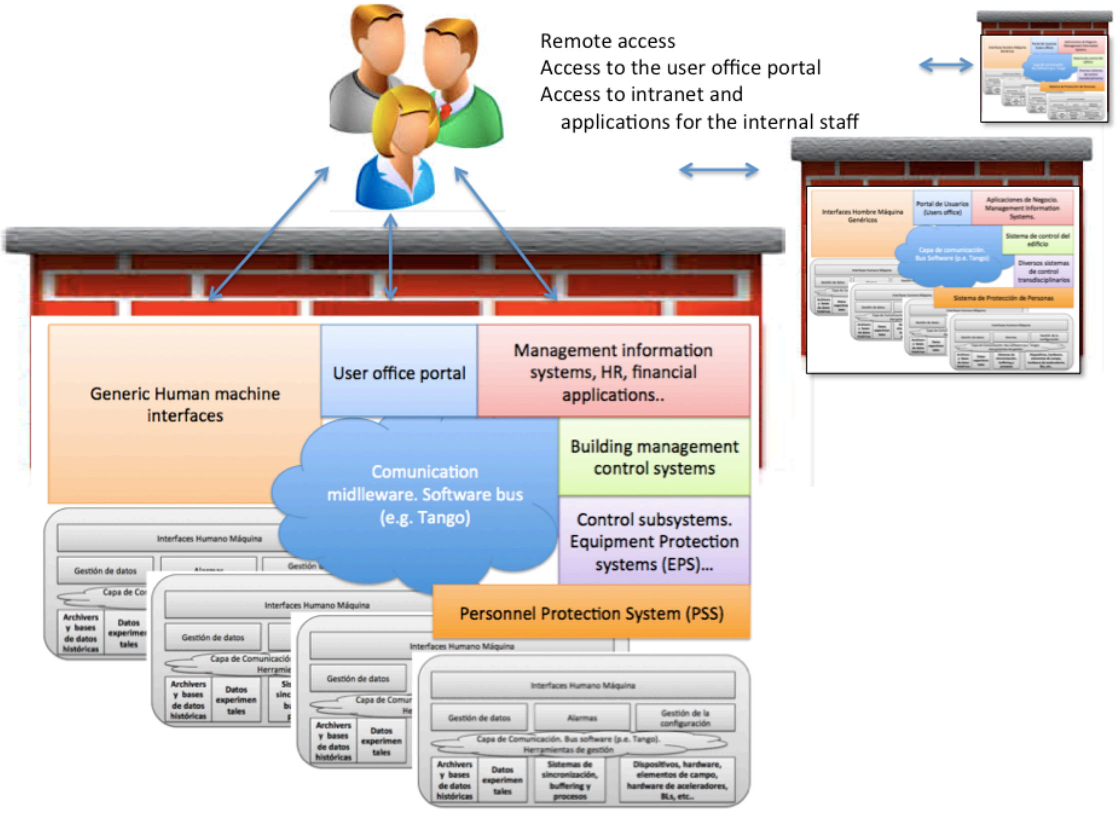


Figure 7-4: Federation of control systems. Users can use different facilities and access remotely to them in order to carry out experiments or access to their data.

In conclusion, except in specific cases occasionally bounded to legal conditions, a Beamline is not designed to work autonomously without network connection. Neither it should be, because the costs of duplicating services and maintenance would be prohibitive. This is the case of all Beamlines at ALBA, the ESRF (except for one already mentioned) and most modern installations.

7.3 Firewalls and industrial firewalls.

Firewalls are devices used to separate different networks, such as a corporate network, an intranet or an external network. Firewalls with packet inspection have also been introduced into industrial environments, complementing the functionality of traditional firewalls. The traditional firewalls work on OSI layer 3 (network) and define basic rules without digging into correlation between packets (Stateful firewalls on the contrary provide this feature). Application level firewalls (OSI layer 7), also known as proxy firewalls, perform a high-level analysis considering protocols and applications; Deep Packet Inspection (DPI) firewalls are common in industrial environments as they implement specific rules for specific protocols, such as OPC or Modbus. The next stage and most extreme are data-diodes, that allow only connections in one direction at the physical level. They behave like real diodes, allowing read-only from the control network while physically forbidding writing. This is extremely resistant to cyber-attacks because the communication in one direction is physically cut off. They can replace in some configurations the traditional DMZ [7:4]. Diodes have a hardware that ensures the one-way transmission and a proxy at both sides of the diode with specific applications for industrial buses such as *Modbus replicator* or *OPC replicator*. Every proxy keeps bidirectional communications with its associated network but it is only one-way through the diode. In this way, bidirectional protocols such as TPC that requires *hand-shaking*" can be managed by the proxy and replicated in the other proxy as bidirectional but using a one-way channel.

7.4 Cryptography and control systems

Nowadays, with the advent and extensive use of wireless communications and the use of IT for every-day confidential business, such as banking, the cryptography became a commodity, present in certificates and digital signatures used by the general public. Cryptography is present in Wi-Fi communications, authentication protocols and of course the web protocols (https). Encryption is the codification of a message in a certain way such as there is an inverse process to decode the original message. As previously discussed, control systems have traditionally relied on physical and logical access control rather than encryption[276]. Encryption is a complex process with a complex setup that may take time and resources. Symmetric keys such as DES[277] or Triple-DES require less resources whereas, asymmetric keys (Public Key Infrastructure[278]: public-private, such as RSA[279]) are generally safer but take more resources; a combination of both such as TLS[280] that uses public key cryptography for the authentication and symmetric

---

[276] Encryption is the codification of a message in a certain way such as there is an inverse process to decode the original message.

[277] DES: Data Encryption Standard

[278] PKI: Public Key Infrastructure: https://en.wikipedia.org/wiki/Public_key_infrastructure

[279] RSA: Rivest–Shamir–Adleman, one of the first public-key cryptosystems and widely used. https://en.wikipedia.org/wiki/RSA_(cryptosystem)

[280] TLS: Transport Layer Security. https://en.wikipedia.org/wiki/Transport_Layer_Security

keys for the encryption is often a good compromise. Encryption is common at the session level, e.g. *Secure Shell* (SSH), but is rare at the communication layers [7:5].
New installations like the Square Kilometer Array (SKA)[281] need to transmit data from antennas kilometers away from the receptors. Wireless communications are intrinsically more vulnerable to attacks such as "*man-in-the-middle*". Encryption is a must when the network is exposed, always the case of wireless networks. There are several alternatives. The option widely adopted in scientific facilities until today is the use of standard encrypted sessions and sockets (available in the OS).

Systems are today increasingly complex and distributed, and users require transparency and friendliness in environments more and more distributed and not anymore restricted to a single facility but interconnecting federated networks and private and public clouds.
The final solution would be adding built-in secure authentication and encryption mechanism to the control systems.

7.5 Authentication and Authorization

The requirements of the control system have also evolved a lot in this aspect. The systems are interconnected with the whole installation, facility, factory or company and potentially accessible remotely from mobile devices. In order to mitigate the problem, certain security measures are taken, often involving encryption and in many cases centered around *Secure Shell* (SSH) to authenticate and authorize the session. Despite of being enough for a large number of cases, in order to provide a good level of usability and a good user experience, this needs to be complemented with other technologies. For example, the user offices, or data catalogues would need a federated *Central Authentication Service* (CAS). Umbrella[282] is a federated authentication system explained in the next paragraph which resulted from a European Union FP7 project: PaNData[283].

7.6 Authentication federation

Providing a good user experience in user offices requires a common authentication mechanism shared between different institutes. Researchers apply proposals to different facilities, including light and neutron sources that can complementary and both needed for a particular research. In order to manage these proposals and the subsequent data, scientists can login to user office portals of the different facilities, data catalogues etc. They could eventually not only

[281] SKA: Square Kilometer Array (https://www.skatelescope.org/)
[282] Umbrella: http://umbrellaid.org
[283] PaNData: http://pan-data.eu/. **P**hoton **a**nd **N**eutron **data** infrastructure initiative. Project funded by the 7th framework project (FP7) of the European commission to create a common base for IT infrastructures in light and neutron sources.

edit and manage proposals but also browse experimental data and perform remote data processing and analysis.
The Umbrella project solves some of these requirements. Umbrella is a federated authentication system for light and neutron sources in Europe. It is a design applied to the existing web based user office portals. It has *an identity provider,* although this can be replicated for availability purposes, and it is based on Shibboleth[284], a software package for "*Web Single-Sign-On*" between organizations. Shibboleth is an open source project distributed under an Apache license. The communication is based on SAML to provide a centralized authentication and attribute exchange. When a particular user tries get access to a resource, the application redirects to the service provider, which asks the identity provider (IdP) about this particular user. The IdP checks whether a session is already open. If not, it authenticates the user by different means such as user-password or Kerberos. The service provider validates the user and creates a session with the appropriate permissions for that user.

The web authentication covers many of the initial requirements for the federation of the authentication. However, federating authentication goes further and needs to include data storage systems and cloud computing amongst others. The Moonshot[285] project uses this technology (based on Shibboleth and Eduroam[286]) to extend the federated authentication to non-web services.

7.7 Security in control systems

In the first installations, control systems were isolated from the outside world. Security relied on a good physical access control, combined with the physical separation between the control network and fieldbuses from the office network and obviously from internet. The paradigm has changed and modern systems are interconnected to the outside world. Remote accesses are frequent and increasingly from mobile devices. Physical access control still applies, but control system networks need to be remotely accessible. Routers, firewalls, DMZs, VLANs and even occasionally data diodes secure traffic from the corporate network to the control system networks. This is valid for scientific installations control systems and for industrial systems, although in the later the authorization is often restricted to a more reduced number of users.
The overall security requires first the authentication of the session. Facilities and industries have directories such as LDAP (common in scientific installations) or Microsoft Active Directory (common in industries) or a combination of both. The authentication is performed by for example user-password combination or more complex systems such as asymmetric Public-Private keys or Kerberos[287].

---

[284] Shibboleth: http://shibboleth.net/about/
[285] Moonshot: https://www.jisc.ac.uk/rd/projects/moonshot
[286] Eduroam: https://www.eduroam.org/
[287] Kerberos: Authentication protocol of computer networks. https://en.wikipedia.org/wiki/Kerberos

The compromise between security and usability is crucial. The most secure network is the one physically isolated; the opposite approach, the most accessible, is interconnecting and opening everything.

The compromise usually goes to keeping the installation secured from the millions of potential cyber-criminals on the internet, but not protecting that much against the tens of people that can gain access to the system from inside; keeping the focus on security on the internet and favoring usability on the intranet.

The federated authentication improves usability to users by sharing data and metadata between the participant facilities. Service providers receive usernames, groups, keys etc. from the identity provider with the consequent risks. The preservation of these data is one of the critical points in the federated authentication. And the authentication is only the first step. The authorization shall be managed accordingly by the different facilities.

7.8 Summary

Cyber-security has never been the highest priority in the design of control and data acquisition systems. In industry, the control networks used to be physically separated without any link from the outside world. The scientific installations used to install independent networks with private IPs and with a very limited remote access. This is no longer the norm, making dedicated security measures mandatory at different levels. Services demand servers with up-to-date antiviruses, patched and up-to-date operating systems and monitored and segmented networks. Authentication and authorization protocols must support remote operation and therefore connections from different networks and mobile devices. This is already a must in modern installations, implementing cyber-security as a transversal discipline that requires permanent resources for monitoring the installation, training professionals and final users, and continuously reviewing the processes.

The paradigm changed in the last decade and the industry considers nowadays controls networks data and access extremely valuable. Data from control networks is precious for the further analysis with big-data and business-intelligence tools and for the continuous improvement in production processes, better diagnostics and resolution of incidents and problems. After all, remote access to data and services fosters the collaboration across different institutes and improves the scientific production. Consequently, the fieldbuses and control networks are or will be no longer isolated from the world, neither in industry nor in scientific environments[7:7]. Cryptography is not yet widely extended and often only applied to sessions (e.g. SSH or NX-SSH) and not to the communication buses, a practice that becomes clearly insufficient when unsecured channels put the production at risk to malicious lawbreakers. Wireless connections or distributed applications that share data across the internet need encrypted communications and therefore the encryption of the communication protocols is progressively being more demanded. These requirements are a challenge from the development, operation and maintenance points of view[7:6].

None of the two most extended open source control systems middleware products -EPICS and TANGO- provide encryption yet. EPICS channel access and TANGO CORBA based protocols provide no encryption and a still embryonic access control. Security measures such as access control or encryption have not been the priority because the security was sufficiently ensured by other means, effective enough for cyber-attacks from the internet but ineffective for attacks from inside, from cyber-criminals or unintentional users with physical access to the hardware. The problem does not come so much from remote access and remote operation, that is already encrypted (e.g. ssh or NX-SSH protocols), but from unencrypted communications through fieldbuses and networks, that today share both physical cables and wireless channels.

7.9 References

[7:1] "Mossad's Miracle Weapon: Stuxnet Virus Opens New Era of Cyber War". Der Spiegel

[7:2] S. Lueders, "Stuxnet and the impact on accelerator control systems", ICALEPCS, Grenoble, 2011.

[7:3] J. Gutleber et al. "The Medasutron Accelerator Control System", Proceedings of ICALEPCS. Grenoble, 2011

[7:4] S. Harris. "CISSP all in one", 5th Edition. McGraw Hill, 2010.

[7:5] J.R.Vacca. "Cyber Security and IT Infrastructure Protection". Elsevier Science, Syngress, 2013.

[7:6] J. Margulies, S. L. Pfleeger, C. P. Pfeeger, "Security in Computing". Fifth edition. Prentice Hall, 2015.

[7:7] S. Lueders, "Control systems under attack", Proceedings of ICALEPCS. Geneva, 2005.

8 FINANCIAL CONSIDERATIONS FOR THE DESIGN, DEVELOPMENT, INSTALLATION, COMMISSIONING AND OPERATION OF CONTROL SYSTEMS

The number of large scientific installations is rapidly growing in particular with relatively new players like China dedicating important amount of resources to the construction and operation of this kind of facilities. On the other hand, in Europe, North America and Japan, the traditional leaders in the field, the number of installations is relatively high, and therefore the competition for resources derives often in the restriction of operational budgets, aiming to the maximization of the scientific results with respect to investment and operational costs. Therefore, nowadays more than ever, the efficiency, the reduction of operational and maintenance costs and the optimization in the project and service management are critical success factors in the strategic plans.

A rule of thumb says that the budget for computing, information technology, supervision, control and data acquisition systems is about 10% of the budget of the whole installation. This depends on different factors and is always subjected to diverse considerations on what is “computing infrastructure” and what is not [8:1]. In any case, this budget can be adjusted depending on the strategy and policies of the institution, such as for example, the use of COTS[288] hardware and software, turnkey systems, or the level of outsourcing of supplies and services.

Construction of the Control System		
CONTRACTS		
Infraestructure-Racks		
INFRAESTRCUTURA CABLING TOTAL	**19.9%**	
NETWORK and STORAGE: CONTROL	**8.9%**	
Cards and other electronics	**10.4%**	
Motors-Icepaps	**3.7%**	
EPS-PLCs	**3.4%**	Inhouse
OutSourced PSS Tunnel	**12.6%**	Outsourced
Personnel and wages	**32.8%**	
others	**8.3%**	
	100.0%	

Figure 8-1: Common breakdown of a budget of a facility such as a Synchrotron.

The 2010-2014 ALBA strategic plan presented the initial 143M€ investment budget (excluding running costs and personnel) of which 11M€ were dedicated to investment in information technology infrastructure, controls system, data acquisition and specific instrumentation[8:2][8:3].

[288] COTS: Commercial Off The Shelf. Product available in the suppliers’ catalogue that can be bought directly as it is.

Most facilities and scientific laboratories, in particular the newest small and mid-size, contemplate tighter construction and operation budgets while keeping very ambitious technical and scientific objectives, with the consequent fine tune of budget lines of all subsystems. This budgetary adjustment applies to most instrumentation, hardware and software domains, although there are always exceptions where the specification of the subsystem requires a certain specific instrumentation where there is little room for negotiation[289].

8.1 Outsourcing and turnkey systems

Any component of a particle accelerator or experimental station could be potentially outsourced or subcontracted as turnkey system. These are usually systems and components considered as not highly strategic, with low added value, such as for example the cable manufacture and installation. However, these outsourced systems can be very specific where the institute cannot afford acquiring such an expertise, such as for example the beamline detectors development, accelerator power supplies amongst others. A cost effective approach suggests tendering most electronic and mechanical components and producing in house only the ones not available in the market, very specific or small components where the call for tenders' paperwork overhead is not reasonable. Common turnkey systems are the control system of the building, the cooling and fluids distribution and control, fire alarm systems or even occasionally the ionizing radiation personnel protection system. These tenders are awarded to companies with a very high expertise in the field, freeing internal resources to be dedicated to other more specific tasks. In all cases, there is the risk of the long-term maintenance, which often ends up assigned to internal teams, assuming the tasks and knowledge that had been delegated to the subcontractors in the first place.

8.1.1 Added value and differentiation

Both highly specific and commodity systems are candidates to be outsourced turnkey. However there is always a core part of the business that is not to be outsourced: the main activity that provides the added value and continuously searches for differentiation. This is often the case of control and data acquisition systems of Beamlines and experimental stations, a figure of merit of the installation as detailed in chapter 4. Control systems not only need to be robust but need to be continuously improved to meet the requirements of incoming experiment proposals, constantly searching for the innovation that would make the difference from already carried out experiments.

[289] The exceptions are usually high added value instruments such as a detector for an experimental station or the accelerators´ beam positioning monitors electronics.

8.1.2 Components

Errors may be fixed at any state, but the later they are detected and corrected, the costlier it may get. Therefore, one of the crucial tasks of the design of the control system is the correct identification and estimation of the components.

- **Racks, installation infrastructure, cables, trays, etc.** A medium size particle accelerator with a distributed control system may comprise several hundreds of cabinets, each with connections with different cable trays and cable types.
- **Computers (*Input Output Controllers* or IOCs)**, for example diskless industrial PCs with specific hardware such as ADC/DAC cards, counter cards, etc. and with the related software distributed across the facility.
  - It can be divided in several contracts. For example, a cost-effective option is to call for tenders the hardware and carry out the configuration, installation and tests with internal resources, acquiring the required knowledge for the later maintenance.
- **Specific diagnostics and data acquisition devices**, such as oscilloscopes, network analyzers, signal generators, CCD/CMOS cameras, beam loss/beam position monitor electronics, etc.
  - Purchasing these devices result often in several hardware specific contracts.
- **Programmable Logic Controllers (PLCs).** They are currently the most cost-effective solution for non-specialized standard industrial devices, such as pressure gauges, flowmeters, temperature sensors. They are also very well adapted to protection systems with thousands of digital input/output signals.
  - The Equipment Protection System (EPS) is interconnected with most subsystems of the installation. It affects and determines the specification of other contracts such as cabling. Newer Personnel Protection System (PSS) often rely on PLCs as well, but unlike other contracts the PSS follows specific conditions, installation and validation processes. PLCs and the relevant field components are also of a different kind, all safety certified.
- **Specialized timing and synchronization systems**. It often requires a hardware deployment with independent ad hoc communication lines. The required nanoseconds or occasionally picosecond resolutions cannot yet be reached with standard communication devices.
  - Again, the hardware is often outsourced, the design and installation of the system tends to be accomplished and supervised by internal resources.
- **Power supplies**. All magnets in the accelerators need power supplies. The requirements are different for the different families, including a high stability with a few parts per million[290], the possibility of defining and synchronizing ramps, pulsed power supplies for the pulsed magnets etc. There are specific cases such as

[290] It is common to find values of 5 ppm (parts per million) with 18 bits resolution.

the correctors power supplies intervening in the fast orbit feedback, or the Booster power supplies ramped at high power and precision that often need to be built custom made. There are also cases where COTS products are appropriate, such as transfer line magnets power supplies or Beamlines' ion chambers power supplies.

    - **COTS** electronics when possible are the preferred choice. They are usually more robust and easier to maintain in the long term. Custom made products find often the difficulty of spare parts and knowledge transfer from the outsourced company (that may discontinue the product or even may go out of business).

- **Motor controllers**. Each experimental station can have about a hundred motorized axes on average, although this number can occasionally be much bigger. These axes are mostly stepper motors for various reasons. They are cost-effective, simple to operate and maintain and they show an excellent behavior holding the positions. The few exceptions may occur when speed, acceleration or torque require the use of other technologies such as servomotors. The motor control as stated in chapter 4, together with the detectors are the most critical elements in the data acquisition process.
    - The selection of motor controllers is one of the most strategic for many reasons, including the budget. There are very economic controllers in the market, for example the PLC based, but typically offer limited possibilities of synchronization and configuration of continuous scans, crucial for the data acquisition systems at the Beamlines.
- **Network components**. The corporative network is normally purchased as a whole. Besides the building and standard communications, the networking systems are also at the heart of distributed control systems, and even more after the fieldbuses have been replaced by the internet of things.
    - There are many options in this huge market. Typically, the cabling and equipment (switches, cores, patch panels, etc.) are purchased, and commissioned with consultancy services and internal resources. This one of the most strategic domains in the IT system administration and cybersecurity that needs to keep the knowledge in-house.
- Detectors. They may be scalars, of one dimension like MCAs (Multichannel Analyzer) or PSDs (Position Sensor Detector); 2D like cameras CCD or Pixel Array detectors, etc.); or N-dimension like a combination of these in time… The detectors are very much dependent on the particular experimental stations as described in chapter 5. They evolve quickly and constantly increase their performance and data acquisition speed. This can go up to very high data rates where the only available solution is to divide the data flow into several separated data acquisition infrastructures and reconstruct the images after the acquisition (post processing). Requirements on the GB/s range are already present.

    - The Beamline or experimental station usually purchases the detectors (on the construction or maintenance budget), although the integration in the control, data acquisition and storage systems may be carried out by the support groups, which favors the standardization.
- **Backup and archive**. Detectors at the Beamlines may produce a large amount of data[291] that needs to be handled, stored, backup and archived. A data storage system capable of receiving hundreds of MB/s (up to GB/s) from several Beamlines simultaneously is a fundamental asset. The complexity of these systems is constantly increasing, so it is the bandwidth and the data processes at the Beamlines. Various systems may be required for various tasks: (1) data storage into disks, (2) data processing, reading and writing back to disks, (3) corporate data, (4) server hosting, virtual machines, high performance computing, etc.
    - This is a common domain to all institutes and facilities. The paradigm however is changing from installations on premises to collaboration with other high performance supercomputer centers or public clouds. The private clouds on premises are also taking over, becoming a common solution particularly convenient when sharing and distributing data and processing tasks across public and private clouds. The great challenge from the purchasing point of view is finding the tools, such as appropriate framework contracts to be able to buy these services (standard IT hardware or services). This is very common in the industry and private companies but it is still very difficult in public organizations in different countries.
- **Cabling**. This is one of the most critical components of the system, due to the volume and the number of details to be considered and documented in the technical specification. However, this is one of the niches most likely to be outsourced. The vast amount of time needed would make it unrealistic with internal resources. Since it includes cables and infrastructures of many different kinds to cover all subsystems in the installation, the technical specifications need a level of detail only available in advanced stages of the design. It is also tightly linked to the corporative equipment and cabling database. In other words, not only the database must be in place, but also the documentation introduced in this database must be in an advanced level of maturity, with the cables, instruments, racks and locations correctly introduced and configured for most subsystems. The IT tools supporting the contract can go up to a full configuration management system with specific documents and drawings for routing cable trays and cables.
    - One single call for tenders that may be divided in different lots, like the power cables in one lot, the network cables in another lot, the motor and encoder cables

[291] See chapters 4 and 5.

in another, etc. The specification and the paperwork associated to this contract take often several person years.

8.2 Standardization and call for tenders

Public calls for tenders involve a complex paperwork and workflows to keep in mind. Specifications shall include a clear and comprehensive explanation of the system or product, with the suitable technical documentation and annexes describing the hardware and software standards and the interfaces to comply with. Figure 8-2 shows a graphical definition of responsibilities to be assumed by the contractor and the home institute to be used and referenced during the duration of the contract and in particular during acceptance tests.

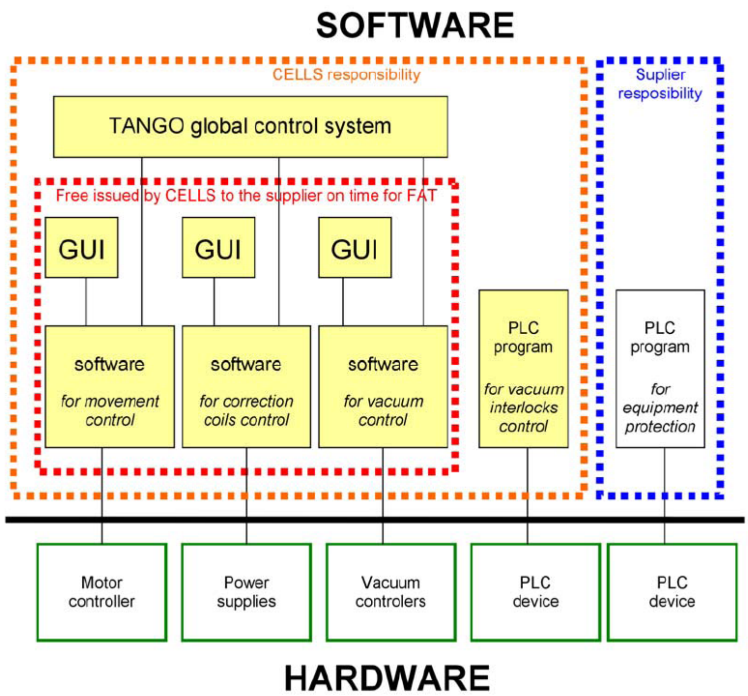


Figure 8-2: Example of definition of responsibilities in a public call for tender. The responsibility of the subcontractor is in blue. Red dots indicate what the institute is responsible for and the orange dots the implication in the acceptance tests.

8.3 Summary

Recent installations often need to handle a greater competition with more ambitious objectives and more limited budgets. The computing, control and data acquisition systems infrastructure manages about a ten per cent of the total budget. Several strategic disciplines are chosen as the candidates to focus the internal efforts on. The strategies of outsourcing and turnkey systems free resources during the installation phase although they are more difficult to maintain in the long-term, and with the time, forcing a full refurbishment according to the standards of the institute. Since a reasonable planning makes impossible to undertake the construction of a facility only with internal resources, a critical success factor consists on what to outsource and what to focus the internal resources on.

Maximizing transversal projects and standards[292], makes easier tendering, commissioning and long-term maintenance. Call for tenders must include maintenance plans when possible[293] and critical contracts may require a specific risk analysis. The maintenance budgets and plans must be included in the executive project of the construction.

8.4 References

[8:1] D. Fernández-Carreiras, D. Beltran, T. Coutinho, G. Cuní, J. Klora, O. Matilla, R. Montaño, C. Pascual-Izarra, S. Pusó, R. Ranz, A. Rubio, S. Rubio-Manrique, R. Suñé. “The design of the Alba Control System: A cost-effective distributed hardware and software architecture”. Proceedings of ICALEPCS 2011 (p. 1318). Grenoble. France.

[8:2] Strategic Plan for CELLS: 2010-2014 (www.cells.es/en/about/strategic-plans/strategic-plan-2010-2014.pdf)

[8:3] Strategic Plan for CELLS: 2013-2016 (www.cells.es/en/about/strategic-plans/strategic-plan-2013-2016.pdf)

[8:4] Strategic Plan for CELLS: 2017-2020 (https://www.cells.es/en/about/strategic-plans/alba-strategy-plan-2017-2020.pdf)

[292] For example transversal subsystems, common to accelerators and Beamlines in a light source, like the case of large interlock and machine protection systems using the same technology, cabling, software, etc.

[293] This depends on the purchasing legislation of the different countries.

9 DATA MANAGEMENT

Scientific installations are inherently prototypes with specific requirements where the successful integration of the state-of-the-art standards and components with the ad-hoc specific designs and innovations is a critical success factor to provide cutting-edge functionalities while controlling the costs. Data management systems can rely on central systems transversal to the organization and/or sometimes dedicated ad-hoc subsystems for specific instruments. Yet in the longer run, there may be synergies, such as central backup or archive systems, general data catalogues and access policies that often favor a centralization. This also relates to the fact that the investment in computing infrastructure (CAPEX[294]) is more and more complemented with services (OPEX[295]), such as custody of copies of backup and archive tapes for disaster recovery; or access to public/private cloud services for data archive, backup and processing.

9.1 Data storage and archive costs. CAPEX vs OPEX

The OPEX schemas make subsequent extensions easier and more flexible, delaying the payments in time when the extended capacity is needed (for example disk space, operational data backup, cold data archives, computing power…). Although the usage of public clouds such as Amazon Web Services (AWS) or Microsoft Azure has been very limited so far in large scientific installations, the use of these services (OPEX) in combination with on-premises computing data centers (CAPEX) has been tested in several institutes, used for some (still small but with a great potential) projects. Public clouds are an alternative that will experience a great growth in the next decade (2020s), with the increase of the network bandwidth connectivity and a considerable reduction of the prices.

9.2 Data policy, remote, open access and the impact on the IT infrastructure

The European light sources are gradually adopting open data policies where "*raw data and associated metadata obtained as a result of public access experiments will be open access after an initial embargo period during which access is restricted to the experimental team represented by the PI*[296]"([297]). The implementation of these policies implies an investment in IT infrastructures but also in software development and collaboration with other institutes. The added value comes out when the data is Findable Accessible, Interoperable and Reusable (FAIR), according to the guidelines on FAIR data management in Horizon 2020[298]. These

[294] CAPEX: Capital Expenditure. https://en.wikipedia.org/wiki/Capital_expenditure
[295] OPEX: Operational Expenditure. https://en.wikipedia.org/wiki/Operating_expense
[296] PI: Principal Investigator
[297] Extracted from the Data Policy declaration at ALBA, derived from the European PaNData project, FP7.
[298] Guidelines on FAIR Data Management in Horizon 2020. Version 3.0. 26 July 2016

principles do not apply only to data but also to the algorithms, tools, workflows, and metadata associated to the dataset [9:1].

The management of different experimental stations, detectors and workflows to produce consistent and complete datasets with the corresponding metadata for their further understanding, process and analysis by third party researchers and software, requires the definition of ontologies, the standardization of metadata and the establishment of public data repositories with catalogues, analysis software and infrastructure associated. Providing public and free access to data and science in general, as defined by the European directives requires to tackle data acquisition, data processing, storage and analysis as a whole and from the roots, integrating logbooks, implementing metadata from application definitions, and creating catalogues and visualization tools for different kinds of datasets and facilities.

There are a few examples going in this direction that can serve as a testbed. MxCube, already mentioned in previous chapters is one of them [9:2]; a SCADA for experimental stations specialized in a particular technique: macromolecules and protein crystallography[299]. It achieved a high level of automation with a deployment in several facilities. It is complemented with ISPyB, a laboratory management system for samples and acquisition processes, to provide automatic (or semi-automatic) data acquisition tools, remote access, so the scientists do not need to travel and be present during the experiment, and standardized de-facto the datasets facilitating its eventual reutilization by other groups, when these and the data policies allow so. This is already possible across Beamlines in different facilities, which is a great achievement (in this discipline, protein crystallography, although the instrumentation varies from one Beamline to another, the processes are very similar and standardized). Extending this level of automation to other disciplines is a complex task due to the variety of stations and techniques and the variety of different experiment types for each technique.

The first step towards open data is a standardization of metadata structures and a data (metadata) catalogue integrated with a user portal. ICAT[300] is an open source metadata management system and catalogue conceived to be generic for a wider range of techniques. ICAT shows a great potential and is referred in most data policies of synchrotrons and neutron sources, but the wide adoption and use by the communities is still under development.

The European Commission has established the basis for open data and open science, favoring the open access to experimental data, and publications. Open and free access to data, algorithms and infrastructures for data analysis, require –besides joining efforts- a high level of standardization at different levels, including data formats, data processing programs and

[299] Also adapted to other techniques at later stages.
[300] ICAT: http://www.isis.stfc.ac.uk/groups/computing/data/about-the-icat-project11690.html

platforms. Formats based on HDF5[301] are spreading across different Beamlines and institutes in the world. The hierarchical representation of the data in n-dimensional blocks adapts well to the structure of scientific data and their metadata. It is more suited than relational databases or other text format like XML, with important limitations in read/write data rates and the sequential process of big datasets of thousands of binary images of several Mbytes.

A data format which speeds up data acquisition and processing is an important step but not enough to share data across institutes, experimental stations and research groups. Datasets from a particular Beamline would need to be compatible with datasets from a similar Beamline – devoted to the same technique- in another synchrotron. NeXuS[302] was created to solve these issues and although present in many institutes across the world did not yet reach the goal of defining and organizing standard metadata (application definition) so that data files and analysis programs can be interoperated between different institutes. NeXuS implements HDF5 (or XML) underneath. Although many facilities use NeXuS-HDF5 with a hierarchical structure of metadata, datasets did not reach the level of standardization for interoperability across different institutes and for different techniques. The unsolved issue and the critical success factor is the definition and standardization of metadata for every experimental technique and the homogenization of data processing interfaces and data analysis so the users can take full benefit from remote access to data and analysis software as a service.

9.3 The new big data and cloud computing paradigms

As of today, every institute has data storage systems, and develop install and maintain software for data collection, processing and analysis. Virtualization, cloud technologies, HPC[303] clusters and in general the so called *Big Data* technologies will contribute to change the paradigm of synchrotron's and other scientific centers' experimental data. Private and public clouds, and platform and software as a service (PaaS and SaaS) technologies are expanding storage systems to new models, federated and more distributed across different institutes.
As a matter of fact, there is a growing need of reusing data taken at different facilities and combine heterogeneous datasets in more complex data analyses. The advent of the cloud computing enables new approaches not possible in the past. Combining private clouds at the facilities and public clouds infrastructures -such as Amazon Web Services, Microsoft Azure- or other players like supercomputing centers, allows a better use of the local infrastructure and a provision of extra resources to cover peak-load needs or even sustained data processing,

[301] HDF5. Hierarchical Data Format. HDFGroup: https://www.hdfgroup.org/HDF5. HDF5 is a binary format and a data model that includes software libraries and visualization tools. It is a free and open software.
[302] NeXuS data format: Data format oriented to photon and neutron sources based on XML and HDF5. http://download.nexusformat.org/doc/html/introduction.html
[303] HPC: High Performance Computing. Supercomputers (often a cluster of computers) with a big computing power.

storage and archive. The harmonization of file formats and metadata ontologies is an empowering condition for the remote data analysis based on traditional techniques. The Big Data technologies bring new opportunities as well. Distributed file-systems across internet and associated systems such as Hadoop[304], or complex search engines such as Elasticsearch (ELK)[305] bring in new approaches to data discovery and data analysis, integration of various information sources, logfiles and big data analytics. The FAIR principles endorsed by the European Commission put emphasis on the discovery and reuse of the data by the machines in addition to supporting its reuse by the individuals. In other words, the FAIR principles will be tightly related to Big Data technologies to increase the social, political and economic impact of the open data and open science.

Although prices and bandwidth of the public clouds do not meet all requirements yet, these are indeed already a good alternative to get access to extra resources during peak loads at reasonable prices. Public clouds cannot get the data streamed at very high speed from the detectors yet, but they are appropriate to do calculation intensive data processing on a given dataset or remote backup and archive for certain amounts of data.

9.4 Python, notebooks and scientific computing

During many years, Fortran has been the preferred choice for scientific data processing and analysis. The main reason was speed at the beginning, later combined with a large library of routines and data analysis specialists trained and experienced within Fortran environments. The field evolved fast and a market was rapidly developed where commercial tools became popular. Examples are Matlab or Mathematica, offering diverse functionalities, numerical computing libraries and visualization tools as well as a programming environment.

Scientific computing has evolved and explored many disciplines other than numerical arrays. Python, with modern notebooks like Jupyter[306] or products like Anaconda offer complete ecosystems adapted to a large number of use cases and scientific needs[307]. Commercial products like Matlab are still widely used in particular fields (such as for example in particle accelerator physics and control systems [9:3]), having the advantage of a better (although costly) support. However, Python related ecosystems, free an open software, even considering the drawback of occasional unmaintained libraries or third party packages, is a suitable –and

---

[304] Hadoop is a framework for distributed data processing written in Java. http://hadoop.apache.org

[305] ElasticSearch is an Open Source search engine developed in Java. https://www.elastic.co. Most referred as Elasticsearch-Logstash-Kibana (ELK), devoted to the analytics of text based logfiles from any source.

[306] Jupyter: https://jupyter.org/; Notebook interface (https://en.wikipedia.org/wiki/Notebook_interface) derived from iPython (https://en.wikipedia.org/wiki/IPython) started by (Fernando Pérez et al.).

[307] Today, Python toolkits are often installed within a large environment providing a collection of packages and tools for scientific computing (Anaconda, Python(x,y) ...)

widely adopted- option. Toolkits such as Silx[308] at the ESRF written in Python (with some libraries like numpy, scipy and Qt …) are experiencing a fast growth within the synchrotron community.

9.5 Machine learning and cloud computing

Artificial intelligence and machine learning have experienced a huge development in the recent years. Major players are Google, Apple, Amazon, Facebook, Microsoft, IBM, etc., who usually keep most of their progress and results private. However, there are a number of open source projects such as Tensorflow (Google, Apache license), caffe (Berkeley, BSD license), mlpy (Fondazione Bruno Kessler, GPL license) … written mostly in Python and C++ offering tools for supervised learning, regression, clustering, etc. with a growing user community.
Machine learning code requires often big computational resources and are often used with computing clusters, GPUs and related frameworks like CUDA[309] for the parallelization and optimization of the algorithms.
These algorithms are good candidates to be executed in the cloud, for example, Amazon AWS, Microsoft Azure or IBM SoftLayer. The advantages of using the cloud services is the availability of the hardware on demand, the large computing power ready to use with support for CUDA, notebooks and the remote accessibility (through ssh for example). On the contrary, as of today, the inconvenient is the complexity billing calculation with the difficulty for budget planning.

9.6 Summary

Although competition between facilities is an underground factor to keep in mind, nowadays all players, international and national facilities, have well understood that collaborations and joint efforts are a crucial success factor. The European Commission has also endorsed these collaborations and reserved budget in the successive framework contracts. It has unified the different services and initiatives in a single project called the European Open Science Cloud (EOSC)[310] with the goal to provide a common directory or collection of data repositories and facilities for open science.

Open data policies require a change at different levels, and the adoption of common data

---

[308] Silx toolkit: https://github.com/silx-kit/silx. A. Solé et al. @ ESRF
[309] CUDA (Compute Unified Device Architecture) is a parallel computing platform and API for GPUs created by Nvidia. It supports C/C++ and Fortran. Python code can also be compiled to be used with CUDA capable interfaces. https://en.wikipedia.org/wiki/CUDA
[310] EOSC: European Open Science Cloud. https://ec.europa.eu/research/openscience/index.cfm . EOSC portal: https://www.eosc-portal.eu/

formats and metadata catalogues go in the right direction but is not enough. The standardization of the metadata, and application definitions is required to increase the level of interoperability, and all FAIR principles in general.

Cloud services have experienced an extraordinary development in the last years, with the advent of Big Data and the competition of the big players for the market niche. Private and in particular public clouds are bringing a great value to scientific facilities, providing services related to data processing and analysis, storage, backup and archive. This is particularly interesting with a common and standard API for different cloud providers and for on premises private clouds. However, there are still some shortcomings to resolve such as the data transfer speeds, price, and the complex billing schemas.

The change of paradigm makes the confidentiality and cyber-security even more critical. Data will not only be in a data center but in the cloud with different copies without a comprehensive track for the customer.

9.7 References

[9:1] Wilkinson, M. D. et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3:160018 doi: 10.1038/sdata.2016.18 (2016).

[9:2] J. Gabadinho, A. Beteva, M. Guijarro, V. Rey-Bakaikoa, D. Spruce, M.W. Bowler , S. Brockhauser, D. Flot, E.J. Gordon, D.R. Hall, B. Lavault, A. A. McCarthy, J. McCarthy, E. Mitchell, S. Monaco, C. Mueller-Dieckmann, D. Nurizzo, R. B. Ravelli, X. Thibault, M. A. Walsh, G. A. Leonard, S. M. McSweeney, “MxCuBE: a synchrotron beamline control environment customized for macromolecular crystallography experiments”. Journal of Synchrotron Radiation. Sep 2010.

[9:3] G. Portmann J. Corbett, A. Terebilo “An accelerator control middle layer using Matlab” Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee.

10 CONCLUSIONS

Control and data acquisition systems in large scientific installations are intrinsically prototypes enforcing the integration of the state-of-the-art standards together with the most recent and innovative solutions in various disciplines, such as project management, IT infrastructures, software development, hardware standardization, configuration management etc. In the XXI century, **TANGO** and **EPICS** have become the leading collaborations in the control system field for the development of open-source frameworks, and **Python** experiencing the biggest growth among the scientific community, in particular for **data analysis** but also for the **control and data acquisition systems**. Using event-based communication has been a natural evolution of the control systems in order to gain efficiency, make the interfaces more responsive, improve the user experience, and the scalability.

The main objectives during the design phase emphasize **performance**, robustness, **cost-efficiency, maintainability** and after all, quality[311]. Budgets are often tight and both **installation** and **maintenance costs** are key requirements and constraints for the project.

New experiments require a faster data acquisition, with a complex synchronization and larger detectors. The flexibility is an essential concept and the standardization of **continuous scans** is a critical success factor for most beamlines. However, there are an increasing number of cases where the experiments are very similar to each other for which the figure of merit is in the **automation** of the data acquisition and the data processing **pipeline**.
The adoption of ITIL best practices, with a formal change management methodology is crucial for the success of the project. It is essential to ensure a consistent service catalogue and a service operation, with a proper **management of requests, changes, incidents and problems**.

A **cost-effective standardization of the instrumentation** reduces the spare part stocks and makes the adaptation of the instrumentation to the control system much simpler. Standards, such as the Input-Output Controllers, **Ethernet as a fieldbus**, **PLCs** for protection systems or in particular the **motor controllers**, are strategic concepts to achieve the excellence and to keep the construction and maintenance costs under control. The standards shall be selected according to the strategic plan and followed by the whole organization. At the same time the must be flexible, and ready for a few exceptions when needed.

Supervision and **control systems generally do not require to be real-time or deterministic.** However, there are processes and subsystems that need a particular determinism for which there are often different alternatives. The most cost-effective solution is often hardware based. Two very significant examples are (1) the protection systems, which are naturally implemented with PLCs interconnected by deterministic fieldbuses or networks often dedicated and (2) the

[311] As a measure of excellence and performance combined with the cost-efficiency and fitness for purpose.

timing systems in charge of synchronizing the injection diagnostics and experiments working at resolution of nanoseconds and in some cases few picoseconds or below[312]. This is addressed with purpose specific protocols, independent hardware often relying on FPGAs, and independent installation with fiber optics, copper cables, switches etc.
Common experiments require **synchronizations between motors and detectors** in the millisecond range or even microseconds in some cases. The figure of merit is not the time resolution, which is largely feasible, but the flexibility to configure and reconfigure different combinations of motors with different combinations of detectors in the **continuous scan**.

Time resolved experiments need detectors with a large frame-rate, synchronized with other detectors and motions at microsecond time resolutions and GBytes/s data rates. Generic data acquisition systems require time-stamping the data acquired with the higher possible precision, for example from protocols like NTP or PTP across all computers intervening in the process.
Multiple detectors are configured in parallel and synchronized to take part in the experiment. They need to be integrated in the control and data acquisition systems and central storage systems, configuring time protocols and network connections with 10, 40 or 100 Gpbs links. This is the technology available today. The next decade will rely on Tbps links and trunks of these links to interface detectors. Big datasets are preprocessed at the beamline and/or at the central clusters at the facility. **Public / private clouds** for storage and data processing are already under tests and will have an important role depending on prices and agreements.

Beamlines and experimental stations are more and more complex and the visitor scientists would prefer to focus in the complexity of the experiment rather than in the complexity of the instrumentation. They only need to know how to perform their experiment, and if possible, once for all facilities. Providing **continuous scans as the standard data acquisition technique is a key issue** in that direction. However it is not straightforward from the hardware and software point of view. The different combinations of synchronization, motion and detectors shall be seamless for the user, and the process shall look as much as possible as the previous equivalent step scans. Users are increasingly moving around different facilities[313] even taking different datasets that are part of the same experiment or the same publication. Therefore, datasets, metadata and analysis processes and programs should be standardized, and the user interfaces and the overall user experience should be shared across different facilities.

Outsourcing and purchasing turn-key systems releases resources in peak-loads during installation, but often, at some point a few years later, these turn-key control (sub)systems need to be (and actually are) rebuilt with standard tools and instrumentation in order to make the

---

[312] Some experiments synchronized between the accelerators and Beamlines may require femto-second resolution and below. This is a challenge for the future generations of photon sources. Free Electron Lasers and Optical Laser installations are addressing these challenges but there is still a long path to explore.
[313] PanData 2016 User Survey. http://pan-data.eu/node/105

maintenance simpler. The lesson learnt is that call for tenders must also include maintenance plans, and for the critical projects a **risk analysis** may also be necessary.
The strategy of conceiving the subsystems from a general perspective also helps to keep the costs reduced. Network or data storage systems are large and transversal infrastructures that could have been tackled independently, for example by Beamline or by subsystem. However, in the longer run there are often synergies, such as central backup or archive systems, that are only possible with a centralized infrastructure.

The combination of PRINCE2 with Agile methodologies such as SCRUM for task and team management empowers the incremental management, the continuous delivery and the fluid communication between clients, customers, developers and managers. The adoption of ITIL best practices for service management enables the continuous service improvement and optimization and is crucial in environments where the same teams are shared between projects and service provision. The appropriate tailoring of the processes, adapted to the service catalogue, service level agreements and support teams is a key factor to avoid the bureaucracy compromising agility.

Control systems need to explore the cryptography and the encryption of the control buses. It had not been considered critical yet, given the fact that there was much to do in other domains and implementing effective measures of network segmentation, authentication and authorization was largely enough to cover the issue. The challenge does not come from remote access and remote operation, that is already encrypted (e.g. ssh or NX-SSH protocols), but rather from the danger of intercepting fieldbuses, that today use both physical cables and wireless networks.

11 FIGURES AND TABLES

FIGURES:

TABLES:

12 APPENDIX A.

Unification of the interfaces for the two dimensional detectors (CCD cameras, MWPD, PADs), carried out at the ESRF.

The CCD interface unification at the ESRF

The CCD cameras are becaming very popular at the ESRF. Most beamlines have one or a lot of them. There are many different types. Frelon, Princeton, Photometrics, Photonics Science, Sensicam, Matrox frame grabber, MarCCD, Mar Image Plate, ADSC, Image Pro (with all the supported) ...

Why so many different cameras?. Because the requirements change a lot from one beamline to another and from one experiment to another.

CCD cameras are often delivered with a software application to operate them (for example WinView for Princeton). In some unusual cases the camera is controlled from that vendor's software, but in most cases it is used from spec either directly, or by running a device server. This is because the camera often needs to be synchronized with other elements in the beamline like motors, counters, shutters, or other CCD cameras...

When a camera is running from Spec via a device server, if Spec does not know about it, a set of macros has to be written. On the other hand, if Spec know about the Device server, One just has to chose the the camera used in the spec config, and that's all.

In order to achieve that, and considering that all CCD cameras have many things in common (despite of the fact that they are different), one "General ESRF CCD" module has been written in Spec.

The only restriction for a Device Server to take advantage of this module is to follow the following list of command names.

D. Fernández Carreiras (rev. 2004)

Command		in	out	Currently in Some Dev Servers
DevState			D_LONG_TYPE	
DevCcdStart	B + 1			DevCCDStartExposure, DevMarCCDstart
DevCcdStop	B + 2			DevCcdAbortAcquis, DevCcdReset
DevCcdRead	B + 3	D_LONG_TYPE	D_OPAQUE_TYPE	DevCCDGetImageData
DevCcdSetExposure	B + 4	D_DOUBLE_TYPE		DevCCDSetExpTime
DevCcdGetExposure	B + 5		D_DOUBLE_TYPE	
DevCcdSetRoI	B + 6	D_VAR_LONGARR[4]		
DevCcdGetRoI	B + 7		D_VAR_LONGARR[4]	
DevCcdSetBin	B + 8	D_VAR_LONGARR[2]		
DevCcdGetBin	B + 9		D_VAR_LONGARR[4]	
DevCcdSetTrigger	B + 10	D_LONG_TYPE		
DevCcdGetTrigger	B + 11		D_LONG_TYPE	
DevCcdGetLstErrMsg	B + 12		D_STRING_TYPE	DevCCDLastError
DevCcdGetXSize	B + 13		D_LONG_TYPE	
DevCcdGetYSize	B + 14		D_LONG_TYPE	
DevCcdSetADC	B + 15	D_LONG_TYPE		
DevCcdGetADC	B + 16		D_LONG_TYPE	
DevCcdSetSpeed	B + 17	D_LONG_TYPE		
DevCcdGetSpeed	B + 18		D_LONG_TYPE	
DevCcdSetShutter	B + 19	D_LONG_TYPE		
DevCcdGetShutter	B + 20		D_LONG_TYPE	

```
DevCcdSetFrames      B + 21 D_LONG_TYPE
DevCcdGetFrames      B + 22                D_LONG_TYPE
DevCcdCommand        B + 23 D_STRING_TYPE  D_STRING_TYPE  DevCCDGetHwPar
DevCcdGetDepth       B + 24                D_LONG_TYPE
DevCcdSetMode        B + 25 D_LONG_TYPE
DevCcdGetMode        B + 26                D_LONG_TYPE
DevCcdSetChannel     B + 27 D_LONG_TYPE
DevCcdGetChannel     B + 28                D_LONG_TYPE
DevCcdSetRingBuf     B + 29 D_LONG_TYPE
DevCcdGetRingBuf     B + 30                D_LONG_TYPE
DevCcdLive           B + 31 D_LONG_TYPE                   DevCcdGrabberLive
DevCcdWriteFile      B + 32                               DevCCDWriteImage
DevCcdReset          B + 33
DevCcdGetIdent       B + 34                D_STRING_TYPE  DevCCDType
DevCcdGetType        B + 35 D_LONG_TYPE
DevCcdSetKinWinSize  B + 36 D_LONG_TYPE
DevCcdGetKinWinSize  B + 37                D_LONG_TYPE
DevCcdSetKinetics    B + 38 D_LONG_TYPE
DevCcdGetKinetics    B + 39                D_LONG_TYPE
DevCcdCorrect        B + 40
DevCcdSetFilePar     B + 41 D_VAR_STRINGARR[5]
DevCcdGetFilePar     B + 42                D_VAR_STRINGARR[5]
DevCcdHeader         B + 43 D_STRING_TYPE
DevCcdSetFormat      B + 44 D_LONG_TYPE
DevCcdGetFormat      B + 45                D_LONG_TYPE
DevCcdSetViewFactor  B + 46 D_LONG_TYPE
DevCcdGetViewFactor  B + 47                D_LONG_TYPE
DevCcdSetHwPar       B + 48 D_VAR_STRINGARR
DevCcdGetHwPar       B + 49                D_VAR_STRINGARR
DevCcdGetCurrent     B + 50
DevCcdGetBuffer      B + 51 D_LONG_TYPE    D_OPAQUE_TYPE
DevCcdGetBufferInfo  B + 52 D_LONG_TYPE
DevCcdReadAll        B + 53
DevCcdWriteAll       B + 54
DevCcdDezinger       B + 55
-------------------------------------------------------------------------------
DESCRIPTION
-------------------------------------------------------------------------------
DevCcdStart             Starts an acquisition
DevCcdStop              Stops and/or aborts an acquisition.
DevCcdRead              Reads an image. Input is number of frame in a serie,
                                        Output a shared array
DevCcdSetExposure       Sets the Exposure time in secs
DevCcdGetExposure
DevCcdSetRoI            Sets the Region of Interest.
                                par[0]=X_begin
                                par[1]=Y_end
                                par[2]=X_begin
                                par[3]=Y_end
DevCcdGetRoI
DevCcdSetBin            Sets the Binning factors
                                par[0]=Y_bin
                                par[1]=X_bin
DevCcdGetBin
DevCcdSetTrigger        Sets the trigger mode
                                Frelon : 1=> Free Run. >1 => external trigger
                                        (this is to keep compatibility between
                                                        Frelon and Princeton)
                                Princeton : 1 =>Free Run,
                                        2=>  CTRL_LINESYNC,
```

```
                                        4=> CTRL_EXTSYNC_PREOPEN (etc)
DevCcdGetTrigger
DevCcdGetLstErrMsg      Gets the last Error message .
DevCcdGetXSize          Gets the horizontal image size (number of Columns)
DevCcdGetYSize          Gets the vertical image size (number of Rows)
DevCcdSetADC            Sets the ADC type (For Princeton)
                                 slow
                                 fast
DevCcdGetADC
DevCcdSetSpeed          Sets the controller speed
DevCcdGetSpeed
DevCcdSetShutter        Sets the external Shutter from the camera
                                1 = yes
                                0 = No external shutter
DevCcdGetShutter
DevCcdSetFrames         Sets the number of frames for each acquisition
DevCcdGetFrames
DevCcdCommand           The Device Server passes the input string directly
                        to the controller and returns the string got from
                        the controller (joker)
DevCcdGetDepth          Gets the number of bits per pixel
DevCcdSetMode           Sets the special working modes . This is a kind of Joker
DevCcdGetMode
DevCcdSetChannel        Sets the input Channel
DevCcdGetChannel
DevCcdSetRingBuf        Sets the number of ring Buffers (Frelon and
                        all cameras using a EDT board). This means DMA ring
                        buffers, not external BIG buffer.
DevCcdGetRingBuf
DevCcdLive              Sets live mode. The device server should be able to
                        put the image in a shared memory to be accessible by
                        dis, spec...
DevCcdWriteFile         Forces the server to write a image to disk.
DevCcdGetIdent          Gets the String that identifies the Camera,
                        device Server and Revision.
DevCcdGetType           Binary code for camera type
                                I.e. Frelon & Internal Serial line
                                        External Serial Line SDV, PDV ...
DevCcdSetKinWinSize     Kinetics window size (Princeton, Frelon)
DevCcdGetKinWinSize
DevCcdSetKinetics       1=>Activates kinetics mode
                        2= > pipeline (kind of special RoI where only few
                             lines are read.
DevCcdGetKinetics
DevCcdCorrect           Corrects the image (MARCCD)
DevCcdSetFilePar        Sets parameters for filenames used by the server.
                        par[0] - absolute root directory
                        par[1] - filname prefix
                        par[2] - image number,
                        par[3] - printf-like image number format (e.g. %03d)
                        par[4] - OVERWRITE flag,y = true, n = false
DevCcdGetFilePar
DevCcdHeader            It passes a string to the device server to be
                        included in the header.
DevCcdSetFormat         Sets the format of the image. This is usefull to
DevCcdGetFormat         Set different formats (edf,  tiff,  gif. The Mar
Scanner uses it to se the different compression modes
DevCcdSetViewFactor     Divide the size of the image to send by factor number
DevCcdGetViewFactor     This is useful when the client only  wants to have
                        a look to the image, but the image is too big, and
```

```
                        it would be a waste of time to transfer the whole image.
DevCcdSetHwPar          Joker to set parameters independent form the camera
DevCcdGetHwPar
                        example :
                                flip value (image mirroring)
                                number of lines lost for kinetics mode
                                ADC working frequency
                                Clocking values , shutter closing time  etc.
DevCcdGetCurrent    Reads current frame being acquired
DevCcdGetBuffer     Reads sinogram. One line of every frame
DevCcdGetBufferInfo     reads timestamps for all frames
DevCcdReadAll           Reads all frames in the same buffer
DevCcdWriteAll      DevCcdBase + 54
-----------------------------------------------------------------------------
STATES                                                          Currently
-----------------------------------------------------------------------------
DevCcdReady     Idle (ready to acquire images)                  DevCcdReady,
                                                                DEVON
DevCcdExposure  Busy (Integrating )                             DevCcdTaking,
                                                                DEVRUN
DevCcdReading   Busy (Reading out the image from camera to DS)  DevCcdTaking,
                                                                DEVRUN
DevCcdSaving    Busy (Saving the image to disk)
DevCcdFault     There is a hdw problem with the controller      DevCcdFault,
                                                                DEVFAULT
Note that 2 more states where introduced (DevCcdReading, DevCcdSaving).
This is because reading out and saving the images can be very slow,
so this is important for the synchronization to get a higher degree
of parallelization..
```

13 APPENDIX. B

Basic definition of the software interface for a particular data acquisition card. The ESPIA card has been developed at the ESRF in collaboration with the hardware manufactured SECAD France.

function name	Parameters	Description
SETTINGS		
espia_open		Opens the device for application access.
espia_close		Closes the device and frees the resources
espia_getsize espia_getccdsize	rows., cols, depth	Gets the current number of rows columns and depth Gets the original ccd size (rows cols adc_depth)
espia_getexposure espia_setexposure	time (ms)	Sets/Gets the exposure time in ms
espia_getringbuffers espia_setringbuffers		Number of the ring buffers managed by the driver
espia_getframes espia_setframes		Sets/Gets the number of frames that the camera will take in a row.
espia_getbinning espia_setbining	row factor column factor	Sets/Gets the horizontal and vertical binning factor
espia_getorientation espia_setorientation		Gets/Sets the image flip
espia_getroi espia_setroi	row_begin, (Y) col_begin (X) no_rows (Y_size) no_cols (X_size)	Gets/Sets the Region of interest (Caution: this must be cross-checked with binning)
espia_setkinetics espia_getkinetics	mode window_size line_beginning number_of_stripes	Gets/Sets Kinetics mode (NOKinetics/Pipeline/FullFrame) (and the other parameters)
espia_getroi espia_setroi	row_begin, col_begin row_end col_end	Gets/Sets the Region of interest (Caution: this must be cross-checked with binning)
ACQUISITION		
espia_start		Starts the acquisition
espia_stop		Stops the current acquisition (and Resets DMA)
espia_check	out = 1 or 0	Returns whether an acquisition is in progress or Idle.
espia_wait	out = image	Waits until the acquisition finishes
espia_read	in= frame_no out = image	Reads an image (image_number)
espia_removetcallback espia_setcallback	callback_function event name	Removes/Assigns a callback function to an event.
espia_reset		Resets the card and the driver. DMA, serial buffers, and registers
SERIAL COMMS		
espia_serput	cmd/register	Sends a string to the camera
espia_serget	value (string)	Reads the serial line from the camera
espia_serreset		Resets the Serial line buffers

STATE		
espia_getstate		Idle. Integrating (exposure). Reading out. DMA. ALARM. i.e. Temperature, power fail … etc. (To be defined by ATE group)

14 APPENDIX. C. RESUMEN EXTENDIDO EN ESPAÑOL

Los sistemas de control de instalaciones científicas son intrínsecamente prototipos dada la propia naturaleza de este tipo de instalaciones. Sin embargo, este hecho no significa que no integren el estado del arte y las más recientes innovaciones en numerosas disciplinas, como gestión de proyectos, infraestructuras, desarrollo de software, estandarización hardware, gestión de la configuración, etc. En esta línea, el sistema de control del sincrotrón ALBA, usado como eje central de este trabajo, se puede considerar como un prototipo de sistema de control basado en TANGO. El Sincrotrón ALBA es la mayor instalación científica en España. ALBA fue el cuarto laboratorio científico en entrar en la colaboración TANGO, después del ESRF, Soleil y Elettra, fue el segundo en estandarizar TANGO para la instalación al completo (aceleradores y líneas de luz), después de Soleil, y el primero en utilizar extensivamente comunicación por eventos (en contraposición a *polling*), y en seleccionar el lenguaje de programación Python como el estándar, prácticas que se irían estandarizando progresivamente con los años en la comunidad científica.

El objetivo principal y las decisiones de diseño se focalizan en la calidad, la fiabilidad en la operación y el soporte a largo plazo. El presupuesto es limitado, por lo que la gestión de presupuesto y los costes de instalación son un requisito primordial a tener en cuenta. Un ejemplo son los chasis para los ordenadores de control de los aceleradores (IOCs). En los aceleradores existentes de referencia, por ejemplo, LHC, Diamond, ESRF, etc. el estándar eran los buses VME de Motorola, con tarjetas del tipo MVME5500 y sistemas operativos determinísticos tipo VxWorks. Estas opciones son muy comunes en instalaciones EPICS. Son robustas, fiables y con un ciclo de vida muy largo. El inconveniente mayor es el precio. En ALBA, estos IOCs, son cPCI de 3U, también sin disco y con tarjetas de CPU Intel tipo ADLINK 3840 con un sistema operativo tipo Linux (original OpenSUSE 11.1), y con significativo menor coste (menos de la mitad).
La estandarización es una clave del éxito. En lo que respecta al sistema de control es esencial para contener el coste total de la propiedad. El sistema de control de ALBA estandariza, sistemas operativos, chasis para IOCs, PLCs, capas de comunicación, interfaces gráficos, lenguajes de programación, sistema de control de versiones de software, repositorios, etc. Sin embargo, el hecho de estandarizar no significa descartar sistemáticamente cualquier excepción. En ocasiones es necesario e incluso beneficioso, siempre que el número de casos permanezca reducido y justificado. En el caso del sistema de control de ALBA, algunos de los estándares con sus excepciones son:

- Sistemas operativos. La operación comenzó con OpenSuse 11.1, en el 2009. Esta distribución fue la primera "*Evergreen*" con un soporte extendido, y continúa en operación más de 10 años más tarde en ciertos IOCs del complejo de aceleradores y líneas de luz. El soporte a largo plazo es un requisito importante. Sin embargo, cambiar de distribución cada cierto tiempo es necesario para mantener el sistema operacional, seguro y actualizado (4-5 años es razonable, aunque dependerá de las necesidades y sobre todo de las carencias del sistema en el entorno actual, por ejemplo, en términos seguridad). Aunque el estándar cubre el 95% de los casos, hay ciertos subsistemas que no se acomodan al estándar, debido fundamentalmente a aplicaciones comerciales o hardware no soportado (drivers inexistentes) en ese sistema operativo. En el sistema de control de ALBA, el 5% de los sistemas utilizan un sistema operativo Windows (inicialmente WindowsXP más tarde migrados a Windows7 con soporte extendido). Prever excepciones de este tipo y contar con un sistema de control multiplataforma es mucho más eficaz y costo-eficiente que intentar forzar el estándar (la plataforma Linux OpenSuse en este caso) sin excepciones. Incluso en plataformas Windows, el soporte comercial de ciertos drivers no sigue el ritmo de distribuciones de Microsoft. En 2020, con Windows 10 estandarizado y el soporte para arquitecturas de 32 bits concluido, todavía existían en el mercado drivers para ciertos instrumentos solo disponibles para 32 bits.

- Chasis para *Input Output Controllers* (IOC). Los Compact PCI con CPU Intel son los estándares. Se estandarizaron tarjetas de entrada y salida para los distintos tipos de señales, intentando minimizar el coste de la propiedad y el mantenimiento. Así, se minimizaron los fabricantes. La mayor parte de las tarjetas y chasis fueron del fabricante ADLINK: ADC 16 bits 4 canales de entrada simultáneos muestreados a 500 kHz (ADLINK2005) y a 2 MHz (ADLINK2010), ADCs con canales multiplexados, canales de salidas analógicas (DAC), entradas y salidas digitales, CPU monoprocesador sin ventiladores para cPCI, PCs industriales, etc. Aunque conviene mantener el estándar en la medida de lo posible, en ocasiones la solución alternativa al estándar aporta más valor y beneficios. En el caso de ALBA se minimizó el número de fabricantes, pero hay excepciones, por ejemplo, la tarjeta de contadores digitales se escogió de *National Instruments*, debido a su flexibilidad y funcionalidades. Otras excepciones comunes vienen de la integración de equipos comerciales, frecuentemente con software propietario que se ejecuta en Windows, con estaciones de trabajo integradas con el equipo etc.
- Programmable Logic Controllers (PLCs). Los sistemas de PLCs son uno de los pilares de los sistemas de control en la instalación. Forman parte de la protección de equipos y/o personas. Son transversales e intervienen en todos los sistemas y subsistemas. En ALBA hay dos sistemas de enclavamientos basados en tecnología PLC claramente diferenciados, el sistema de protección de equipos (EPS) y el sistema de protección de personas (PSS). El EPS se basa en PLCs de B&R, distribuidos en 50 CPUs y más de 100 periferias distribuidas en el complejo de aceleradores, gestionando más de 7000 señales con su correspondiente lógica, y mantenimiento de cables, conectores etc. Cada línea de luz tiene un PLC con una o varias periferias distribuidas por cabina. La estandarización de los PLCs viene

asociada también con la optimización de los buses de campo. Dependiendo del modelo de PLC se favorece un tipo de bus u otro. Aún así, en ciertas ocasiones es imposible estandarizar porque los criterios son distintos para distintos subsistemas. El PSS utiliza PLCs de Pilz, compatibles SIL3 en la norma IEC 61508. Ésta es la razón principal que hizo escoger tecnologías y fabricantes distintos para estos dos sistemas. No sólo fueron éstas las diferencias, sino que el PSS fue subcontratado y el EPS desarrollado internamente, el PSS se focaliza en la seguridad a todos los niveles, no sólo SIL3, sino que tiene una instalación independiente, con hardware e infraestructuras independientes, mientras que el EPS se integra en la instalación del sistema de control como un componente más. El mantenimiento de los sistemas de protección / enclavamientos es un tema esencial en la instalación, debido a su gran tamaño, a su transversalidad y a su criticidad. A pesar del alto grado de estandarización tanto en el hardware como en los procedimientos de instalación y mantenimiento, en el sistema de control cohabitan otros fabricantes de PLCs; Siemens principalmente, pero también Allen-Bradley o Phoenix-Contact, instalados en sistemas llave en mano como el Linac, fuentes de alimentación o sistemas de radiofrecuencia.

- Las comunicaciones se basan en Ethernet es tanto para la red corporativa como a nivel de buses de campo y redes del sistema de control y adquisición de datos. Implementando los estándares de seguridad, segmentación y virtualización de redes y proveyendo hardware específico en alguna excepción, como las redes determinísticas de PLC se consigue un rendimiento acorde con los requisitos y costo-eficiente.
- Controlador de motores. Cada Beamline puede contener del orden de 100 motores. Esta es la tónica en las líneas actuales en ALBA. Sin embargo, los requisitos en cuanto a elementos móviles no dejan de crecer. Así, en el ESRF el programa de actualización de las Beamlines trajo consigo un aumento en longitud, en el número de elementos y en la complejidad de las estaciones experimentales y ya cuenta con estaciones experimentales con más de 300 ejes. En este escenario, un sistema estandarizado de control de motores, que permita sincronizar el movimiento de varios ejes, enviar o recibir señales de sincronización basadas en la posición y gestionar trayectorias es hoy una ventaja, que en un futuro próximo será un requisito fundamental; el ESRF creó el sistema IcePAP [4:17], y ALBA se unió al poco tiempo, estandarizando toda la instalación con este paradigma desde su fase de diseño, incluyendo Aceleradores, Dispositivos de Inserción y Beamlines, y facilitando de este modo el desarrollo de los *"scans"* continuos.
- Base de datos corporativa de la instalación: Disponer de una base de datos de dispositivos y cables para la instalación ha demostrado ser una ventaja competitiva fundamental, tanto durante la ejecución de licitaciones de cableado e instrumentación como para el mantenimiento general de la instalación. El

repositorio central mantiene el estado de toda la instalación hardware con la documentación y las intervenciones asociadas.

Presupuestos:
Los presupuestos son cada vez más ajustados. La infraestructura de computación y control supone generalmente un diez por ciento de la instalación, aunque puede estar distribuido en distintos centros de coste. La subcontratación y los proyectos llave en mano liberan recursos durante la instalación, pero frecuentemente suponen un problema con el mantenimiento a largo plazo. Las licitaciones también deben de incluir planes de mantenimiento y en ocasiones es necesario realizar un análisis de riesgos en el caso de los contratos más críticos. El plan y el presupuesto de mantenimiento debe de realizarse en el proyecto ejecutivo de construcción.
La estrategia de concebir los sistemas desde una perspectiva centralizada generalmente ayuda a mantener los costes controlados. Por ejemplo, el procesamiento y almacenamiento de datos son disciplinas transversales que podrían tratarse individualmente en cada línea de luz, pero sin embargo, probablemente se redundarían costes por ejemplo en la infraestructura de acceso a los datos, visualización, backup y recuperación etc. y por consiguiente es a menudo más costo-eficiente una infraestructura centralizada.

Innovación:
La competencia por la financiación entre institutos de investigación hace que la innovación y la diferenciación sean claves fundamentales del éxito del proyecto. En Alemania y en Estados Unidos se están cerrando grandes instalaciones consideradas redundantes para liberar fondos para otro tipo de instalaciones. La instrumentación y los sistemas de control y adquisición de datos son disciplinas decisivas en el avance y la diferenciación de los experimentos llevados a cabo en las estaciones experimentales. En lo que respecta a los aceleradores, el ajuste de los modos de inyección, y los patrones de distribución de los electrones en los anillos de almacenamiento junto con el avance en las posibilidades de sincronización y la conexión entre la sincronización de las Beamlines y los aceleradores es uno de los desafíos y uno de los dominios en los que se pone y se pondrá más esfuerzo en los próximos años.
En plena ebullición de iniciativas de libre acceso a los datos y a la ciencia en general, los formatos de datos, los metadatos y los protocolos de adquisición procesamiento y análisis y la integración con las tecnologías de la nube (cloud) y la inteligencia artificial requieren estandarización. Así se facilita la comunicación entre científicos de distintos grupos y se homogenizan programas de análisis de datos entre diferentes disciplinas. Los formatos de datos basados en HDF5[314] se están popularizando en diferentes Beamlines y entre los distintos sincrotrones de todo el mundo. HDF5 es un formato de datos binario (y modelo de datos, que incluye librerías de software y programas accesorios para visualización, configuración y análisis) de código abierto y software libre. La representación jerárquica de los datos, en

[314] HDF5. Hierarchical Data Format. HDFGroup: https://www.hdfgroup.org/HDF5

bloques n-dimensionales se adapta perfectamente a representaciones de datos científicos complejos con sus metadatos. En cualquier caso aventaja a otros formatos como bases de datos relacionales o texto XML, que están muy limitados en escritura y procesamiento secuencial de registros en volúmenes de datos grandes (velocidad de lectura y escritura de miles de imágenes y análisis de datos de varios GBytes).

Un formato que acelere la velocidad de adquisición y de procesado de los datos no es suficiente. Se necesita una estructura común que permita compartir datos entre distintos institutos y usuarios. Datos de una Beamline de difracción de polvo, por ejemplo, deberían de ser compatibles con otra de otro sincrotrón o incluso una Beamline de difracción de polvo en una fuente de neutrones. Con este propósito nació NeXuS[315], aunque después de ya más de una década y con presencia en muchas instalaciones no ha conseguido conseguir el objetivo de disponer de formatos de ficheros de datos con una organización de metadatos estándar y homogénea entre distintos laboratorios (para una determinada técnica) a tal punto que puedan compartir software de análisis de datos. Aunque el estándar de datos HDF5 se está consolidando, la estructura de Metadatos dentro de la estructura de árbol de los ficheros todavía no se ha conseguido estandarizar ni entre distintos institutos ni para distintas técnicas, limitando así la utilidad del modelo. La definición y estandarización de metadatos para cada técnica experimental así como la homogenización de los programas de adquisición que permitan el análisis de datos remoto y faciliten la tarea al usuario final es la clave del éxito y donde se focalizarán los esfuerzos.
Las tecnologías de *cloud* privadas, los *clústeres* para HPC[316] y en general lo relacionado con lo que se ha empezado a llamar *Big Data* desembocarán en grandes almacenes de datos en la red (o en federaciones de institutos) disponibles en línea para los que se requieren programas de tratamiento de datos comunes.

Los sistemas de control en instalaciones científicas avanzan en la dirección de integrar formatos estándar, y fomentar las colaboraciones y el software libre de código abierto. TANGO y EPICS son buenos ejemplos de esta tendencia y son actualmente las opciones preferentes para construir sistemas de control de instalaciones científicas.
Ambos TANGO y EPICS funcionan cada vez más sobre plataformas estándar. EPICS requería inicialmente sistemas operativos en tiempo real como VxWorks, pero los soft-IOCs una virtualización de los IOCs implementadas en sistemas operativos convencionales, se van popularizando e imponiendo. Los sistemas de control no necesitan ser determinísticos. Sin embargo, existen procesos que necesitan una solución determinista. Ésta es típicamente hardware. Los dos ejemplos más significativos son: los sistemas de protección de equipos o personas, que se resuelven de manera natural con PLCs y buses o redes determinísticas

[315] NeXuS data format: Scientific data format for light and neutron sources based on HDF5 and XML. http://download.nexusformat.org/doc/html/introduction.html
[316] HPC: High Performance Computing.

dedicadas; y el sistema de sincronización (*timing*) del acelerador que se resuelve con hardware dedicado y desarrollado a tal efecto mediante FPGAs, transmisiones por fibras ópticas dedicadas y protocolos específicos.
En ocasiones, las Beamlines demandan requisitos muy concretos. Como sincronizaciones de detectores con determinados pulsos de electrones del acelerador (*pump and probe*), en la que se combinan una excitación de la muestra (*pump*) y una medida (*probe*). Los requisitos de precisión de tiempos pueden llegar al orden de picosegundos, lo cual representa un desafío para la electrónica y la distribución de eventos en un radio de centenas de metros. En este tipo de casos se requiere un proyecto y un desarrollo específico. Sin embargo, lo más habitual es que los experimentos requieran sincronización de detectores y motores con precisiones de centenas de microsegundos e incluso de milisegundos. La precisión de tiempos es asequible, sin embargo debe de ser muy flexible para combinar motores y detectores de cualquiera de las formas posibles. En este contexto se aplican los *scans* y en particular los *scans* continuos.
Los *scans* continuos son el núcleo de los sistemas de control y adquisición de datos para estaciones experimentales modernos. No sólo se aplican a fuentes de luz sincrotrón sino que también son extensibles a fuentes de neutrones y otros laboratorios. Los experimentos con resolución temporal necesitan detectores con una cadencia de adquisición alta, sincronizados con otros detectores y movimientos. Esto se traduce en requerimientos de resolución temporal de microsegundos (o menores) y velocidades de adquisición que llegan a GBytes/s e incluso recientemente se están poniendo a punto detectores que pueden producir terabytes por segundo y que necesitan un cambio de paradigma en la infraestructura de adquisición y almacenado de datos. También en la visualización y el análisis.
A nivel software, los datos para su procesado y para la gestión de la cadena de adquisición requieren una marca de tiempos cuando se adquieran "*timestamp*", con lo que todos los ordenadores deben de estar sincronizados por una base de tiempos global (NTP es necesario y el protocolo PTP, más preciso, es deseable para el futuro).
Los detectores de las Beamlines, se configuran en paralelo y se sincronizan para que intervengan en un mismo experimento. Llegan a manejar tal cantidad de datos que se entregan con su propio ordenador (o en ocasiones pila de ordenadores) para la adquisición de datos. Estos ordenadores suelen tener una conexión (o varias) de fibra óptica dedicada al sistema de almacenamiento en el centro de datos. Aún así, los detectores precisan una línea de sincronización para el experimento, y una sincronización de tiempos de las estaciones de trabajo.

La combinación de PRINCE2 con metodologías AGILE como SCRUM para la gestión de tareas y del día a día de los equipos empodera la gestión incremental, automatización de los despliegues y la fluidez en la comunicación entre los clientes y los gestores de proyecto e ingenieros y programadores. La adopción de las buenas prácticas ITIL para la gestión de servicios facilita la gestión de la demanda y de la capacidad, la gestión de incidencias y peticiones y en definitiva la mejora continua de los niveles de servicio. Es particularmente importante en entornos donde los equipos están compartidos entre desarrollo de proyectos y gestión de servicios. Al mismo tiempo, la adaptación de los procesos al catálogo de servicios es fundamental para agilizar la gestión y la satisfacción de los usuarios.

En la nueva fase en la que entramos en la década de 2020, los sistemas de control necesitan explorar la criptografía para incrementar la seguridad dentro de los buses de campo y control. Ya no bastará con la protección de las redes, autenticación, autorización, y monitorización en los sistemas de seguridad convencionales de redes. Hasta ahora, la criptografía no ha sido considerada como prioritaria, porque el cifrado estándar y las estructuras de claves publicas han sido suficientes. Los desafíos no están tanto en el acceso o la operación remotos que ya están cifradas y aseguradas, como en los riesgos de intercepción de buses de campo de sistemas de control transmitidos tanto por radiofrecuencia como por cable.

15 GLOSSARY, ACRONYMS AND ABBREVIATIONS

Accelerator: Also known as “The machine” refers to the particle accelerator complex (electrons, positrons, protons…). It is often composed by more than one particle accelerator.

ACL: Access Control List.

ADC. Analogue to Digital Converter.

ADU: Analog to Digital Unit. Basic digital unit (that can be distinguished) after the analogue-to-digital conversion stage.

AdvancedTCA (and MicroTCA): Also known as ATCA and uTCA: Specifications carried out by the PCI Industrial Manufacturers Computers Group: https://en.wikipedia.org/wiki/Advanced_Telecommunications_Computing_Architecture

Afterglow: (Detectors) The temporal remaining effect after an exposure or an excitation. This has an effect on the effective deadtime of the data acquisition time.

Agile: It is a set of values and principles for the software development (or in general project management). It defines software development methods based on frequent interactions with the users.

ALBA: Synchrotron in Cerdanyola del Vallès, Barcelona, Spain. http://www.cells.es/en

APD: Avalanche Photo-Diode.

API: Application Program Interface: Public Interfaces to the functionalities of a particular software.

AppleTalk: Network protocols by Apple. Discontinued.

AS: Australian Synchrotron, Melbourne, Victoria, Australia. http://www.synchrotron.org.au/

ASIC: Application Specific Integrated Circuit.

AT&T: American Telephone and Telegraph.

AWS: Amazon Web Services. Public Cloud.

Backlog: Refers to the list of tasks or pending tickets.

Bazaar: Version control system. http://bazaar.canonical.com/en

Beamline: Instrument with focalization mirrors, monochromator, sample environments and detectors where the experiments are carried out.

BER: Bit Error Rate. Number of bit errors per transmitted unit. https://en.wikipedia.org/wiki/Bit_error_rate

BESSY II: Synchrotron in Berlin, Germany. https://www.helmholtz-berlin.de/quellen/bessy/index_en.html

Binning: (2D Detector) Grouping pixels in the detector (for example a CCD) in a way that two or more pixels are read and digitalized together reducing the size of the image and increasing the acquisition in the same proportion.

BESSY II, Berlin, Germany. https://www.helmholtz-berlin.de/quellen/bessy/index_en.html

Booster: (pseudo) Circular (polygon) particle accelerator that bring the particle beams to the nominal before the injection in the Storage Ring.

BPM: Beam position Monitor. Usually consisting of two or four channels in order to give values in both horizontal and vertical axes.

B&R Automation. Austrian company providing sensors PLC and other electronic devices. http://www.br-automation.com/en/

BTS: Booster to Storage Ring transfer line.

Bump: The distortion applied by the injection kickers to the electron beam orbit.

Bump bonding: is a technique that assembles 2 chips connected by purpose specific connection points ("bumps").

Bunch (electron or proton bunch). Group of particles in which the beam is divided (pulsed because of the radiofrequency acceleration effect (with the same frequency).

Business Case: Theme of the PRINCE2 methodology. Key document in project management to assess the options and feasibility of a project.

CAMAC: Computer Automated Measurement And Control. Chassis for data acquisition cards. Extensively used in the 80s. Discontinued.

CAPEX: Capital Expenditure: https://en.wikipedia.org/wiki/Capital_expenditure

CAS: Central Authentication Service.

CBF: Crystallographic Binary File. File format used in protein crystallography. It is a binary format with a header. Complementary to CIF (Crystallographic Information File) in ASCII format.

CCD. Coupled Charged Device: https://en.wikipedia.org/wiki/Charge-coupled_device

CERN. European Center for particle physics, Geneva, Switzerland: https://home.cern

CLI: Command Line Interface. Text based interfaces such as SPEC o SPOCK (Sardana).

CMOS: Complementary Metal-Oxide-Semiconductor. Technology to manufacture integrated circuits: https://en.wikipedia.org/wiki/CMOS

CODAC. Control and Data acquisition Systems.

Computer worm: Self replicated software that expands autonomously on the network.

CORBA: Common Object Request Broker Architecture. Standard object oriented communication infrastructure to develop distributed software applications.

CORBA IOR: (Interoperable Object Reference).

COTS: Commercial Off The Shelf. Product available in the suppliers' catalogue that can be bought directly as it is.

CRATE: Rackable chassis to install different types of electronics.

CSN: Consejo de Seguridad Nuclear. Spanish Nuclear Safety Council.

CSM: Charge Summing Mode. Feature of some detectors such as PADs to divide and assign the charge to different pixels more precisely.

CUDA (Compute Unified Device Architecture) is a parallel computing platform and API for GPUs created by Nvidia. It supports C/C++ and Fortran. Python code can also be compiled to be used with CUDA capable interfaces. https://en.wikipedia.org/wiki/CUDA.

CVS. Concurrent Versions System. Version control system (obsolete nowadays).
https://en.wikipedia.org/wiki/Concurrent_Versions_System

CSUC: “Consorci de Serveis Universitaris de Catalunya”. IT network and communications public services for universities in Catalonia, Spain.

DCCT: Direct Current, Current Transformer.

DCS. Distributed Control System. In some circumstances it can refer to Detector Control System (such as big detectors like ATLAS at CERN).

Dead time: (detector) Is a concept related to the intrinsic physics of the detector and its capability to acquire photons. Sometimes it may refer to the whole data acquisition chain.

DECTRIS: Spin-off from the Paul Scherrer Institute in Switzerland and today a marked leader in silicon detectors for synchrotrons: http://www.dectris.com

DES: Data Encryption Standard. Obsolete and replaced by Triple-DES.

DESY: Deutsches Elektronen-Synchrotron. National research center in Hamburg, Germany. http://www.desy.de

DHCP: Dynamic Host Configuration Protocol.

DLL: Dynamically Linked Library.

DLS: Diamond Light Source. Synchrotron nearby Oxford, U.K.

http://www.diamond.ac.uk/Home.html

EDF: ESRF Data Format used at the ESRF and other institutes like ALBA with a fixed size ASCII header for metadata and a binary encoding for the data. Typically used for 2D images.

EDS o EDX: Energy Dispersive X-ray spectroscopy.

Eduroam: Wifi authentication technology based on the IEEE 802.1X standard and a hierarchy of RADIUS proxy servers. https://www.eduroam.org/

ElasticSearch: Open Source search engine developed in Java. https://www.elastic.co

Elettra Sincrotrone: Synchrotron in Trieste. Italy. https://www.elettra.trieste.it

ELI: Extreme Light Infrastructure. It has three pillars in Czech Republic, Romania and Hungary (ELI-ALPS) financed with European funds.

Encoder: Device to measure the angular or linear position.

EOSC: European Open Science Cloud. https://www.eosc-portal.eu/

EPICS. Experimental Physics and Industrial Control System.

EPS: Equipment Protection System.

ERP. Enterprise Resource Planning.

ESF: Edge Spread Function.

ESPIA: ESRF-SECAD-PCI-Image-Acquisition: See Appendix B for details of the ESPIA card.

ESRF. European Synchrotron Radiation Facility. Grenoble, France: www.esrf.eu

EtherCat: Open source protocol for the use of Ethernet in industrial environments. The technology was initially developed by Beckhoff.

Ethernet PowerLink (EPL). Open source deterministic network protocol originally developed by B&R.

FAIR: Findable Accessible, Interoperable and Reusable. Principles to open data to public access.

FCT: Fast Current Transformer.
FEL: Free Electron Laser. See XFEL (X-Ray Free Electron Lasers).
FET: Field Effect Transistor.
Firewalls: Network devices that act as barriers, filtering protocols and ports, and preventing unauthorized communications between networks.
Flat field: (2D detector) Defined as the image taken of the beam without the sample to get the imperfections of the optics and the detection system for further normalization (division). Not all techniques allow taking flat fields.
FOSS: Free and Open Source Software.
FPGA: Field Programmable Gate Array.
FreeBSD: Berkeley Software Distribution. Unix like operating system developed at Berkeley University.
Front-End (synchrotron): Vacuum chamber with diagnostics and the necessary instrumentation to transport the photon beam from the Storage Ring to the beamlines.
FS. Fluorescence Screen.
FTA: Fault Tree Analysis.
Géant: Public European network for education and research.
Git: Software version control system created by Linus Torvalds for the Linux version control and nowadays the most used around the world. https://en.wikipedia.org/wiki/Git
GPL: GNU Project Public License. Free Software Foundation.
Grating monochromator: Silicon crystal with a coating of different materials that has a periodic pattern that splits and diffracts the beam into several directions. There are several types depending on the structure for different applications. They are extensively used in soft X-rays Beamlines.
GUI: Graphical User Interface. A type of human machine interface graphical based.
HDB: Historical Database. Database to store and manage historical engineering values.
HDF5. Hierarchical Data Format. HDFGroup: https://www.hdfgroup.org/HDF5
HMI: Human Machine Interfaces.
HPC: High Performance Computing.
HTML: Hypertext Markup Language.
HTTP: Hypertext Transfer Protocol:
https://en.wikipedia.org/wiki/Hypertext_Transfer_Protocol
HVAC: Heat Ventilation and Air Conditioning. Control systems for buildings.
ICAT: Metadata management system:
http://www.isis.stfc.ac.uk/groups/computing/data/about-the-icat-project11690.html
IcePAP: Motor controller. Project initiated at the ESRF by P. Fajardo and J.M. Clement Today it is a collaboration of several institutes including ALBA and MAXIV.
Icinga: Tool to monitor and manage the alerts in computers derived from Nagios.
ID: Insertion Device. Used to produce high intensity photon beams from particle accelerators. Used in Synchrotrons and Free Electron Lasers.

IgorPro: Commercial software for data analysis, numerical computation and graphical interfaces.

InnoDB: Storage engine for MySQL. Set as default in the latest versions replacing MyISAM: https://en.wikipedia.org/wiki/InnoDB

Instrumentation Technologies (I-Tech): Slovenian company specialized in beam position monitor electronics for particle accelerators: http://www.i-tech.si

IOC: Input Output Controller. From the EPICS terminology. Usually a computer that performs an action related to the field, sensors or actuators.

IoT: Internet of Things. Autonomous sensors or devices connected by a network (often wireless).

IOT: Inductive Output Tube. Kind of high power RF amplifier.

IPython: Command shell for interactive computing developed in Python https://en.wikipedia.org/wiki/IPython by Fernando Pérez et al.

IQ: In-phase Quadrature. Representation of a sinusoidal signal with 2 sinusoidal amplitude modulated and with a $\pi/2$ rad phase. IQ is extensively used in electrical engineering and regulation systems.

IRQ: Interrupt Request. Hardware signal addressed to the CPU to temporally interrupt a process.

ISO: International Standard Organization.

IT: Information Technology.

ITER. International tokamak: https://www.iter.org

Jenkins: Free software for continuous integration. https://jenkins-ci.org

JIRA: Jira is a software developed for service and project management developed by ATLASSIAN. https://www.atlassian.com/software/jira

Jitter: fluctuation in the generation or transmission of the signal, perceived as an imprecision in the reception or the trigger.

Jupyter: Notebook interface (https://en.wikipedia.org/wiki/Notebook_interface) derived from iPython started by (Fernando Pérez et al.). https://jupyter.org/.

Kerberos: Authentication protocol of computer networks. https://en.wikipedia.org/wiki/Kerberos

Kicker: High voltage and current with short pulses dipolar magnets used for injection in particle accelerators.

Linac: Linear accelerator.

LDAP: Light Weight Directory Access Protocol.

LEP: *Large Electron Positron Collider*. Operated at CERN from 1989 to 2000.

LGPL: Lesser Gnu Public License

LHC: Large Hadron Collider. In operation at CERN.

Libera:Electronics for beam position monitoring built and commercialized by I-tech, Slovenia. BPM. http://www.i-tech.si

LLRF: Low Level RF: RF Phase and amplitude regulation system.

LP: Line Pairs: Parameter used to measure the resolution (lp/mm) or frequency (lp/cycle) of an optical system.

LSF: Line Spread Function.

Mathematica: Mathematical analysis and calculus commercial software package.

Matlab: MATrix LABoratory. Software tool developed initially oriented to mathematical calculus

MaxLab. Synchrotron laboratory in Sweden.

MAXIV. Synchrotron in Sweden in operation since 2016.

MB/s: MegaByte per second.

MedAustron: Cancer therapy accelerator in Austria: http://medaustron.at/en

MIS: Management Information Systems.

Moonshot: https://www.jisc.ac.uk/rd/projects/moonshot

MRF: Micro Research Findland. Finish company specialized in electronics for timing and synchronization. http://www.mrf.fi

MTBF: Mean Time Between Failures.

MTF: Modulated Transfer Function.

MWPC: Multi Wire Proportional Chamber. 2D Detector made of wires setup in both planes.

MyISAM: Storage engine for MySQL: https://en.wikipedia.org/wiki/MyISAM

MySQL: Open source BDMS acquired by Sun and later by Oracle.

Nagios: Open source tool to monitor and manage the alerts in computers.

NAS: Network Attached Storage.

NCD: Non Crystalline Diffraction.

NEXUS: NeXuS. Data format for X-ray and Neutrons experiments. Based on HDF5.

NFS: Network File System.

NIM: Nuclear Instrumentation Module. Type of chassis for data acquisition and instrumentation cards.

NIST: National Institute of Standards and Technology.

OPEX: Operational Expenditure. https://en.wikipedia.org/wiki/Operating_expense

OS9: Deterministic real time multitask operating system.

OSI: Open Systems Interconnection Model.

PAD. Pixel Array Detectors.

PaNData: Photon and Neutron data infrastructure initiative. European Framework Program 7 project to create c common base for IT infrastructures in Photons and Neutrons installations. http://pan-data.eu

PaaS: Platform as a Service.

Penning gauge: Device to measure very low pressures (very high vacuum ~ 10^{-12} mbar).

Petra-III: Synchrotron in DESY, Hamburg, Germany. http://photon-science.desy.de

PFD: Probability of Failure on Demand.

PI: Principal Investigator.

Picomotor: Motor (with a rotor) based on the piezoelectric effect.

PID: Proportional, Integrative, Derivative. Device/software algorithm used in regulation systems.

PID: PRINCE2 project management methodology: Project Initiation Document.

Piezo actuators: Positioning devices with very low ranges (based on the piezoelectric effect).

Pirani: Pressure gauges for low vacuum (from 1 to10^{-4} mbar).

PKI: Public Key Infrastructure: https://en.wikipedia.org/wiki/Public_key_infrastructure

PLC: Programmable Logic Controller.

Plugin: (o plug-in) software component to add a specific function to a software application.

PMBOK: Project Management Body Of Knowledge.

PMI: Project Management Institute.

PRINCE2: PRoject IN Controlled Environments.

Product Owner. One of the 3 roles defined in the Scrum Agile methodology.

ppm: Part per million.

PSI: Paul Scherrer Institute (http://www.psi.ch). Villigen. Switzerland.

PSF: Point Spread Function.

PSS: Personnel Safety System.

Public Clouds: IT capabilities (storage, computing power, application hosting etc.) offered as a service and commercially available (datacenters and resources managed by a third party company).

PWM: Pulse Width Modulation.

Pypi: Software repository for Python: https://pypi.python.org/pypi

Python: An interpreted programming language available for a number of platforms.

QRA: Quantitative Risk Analysis.

Qt: Framework multiplatform to develop graphical Human-Machine interfaces and manage graphical applications: https://www.qt.io

Rack: Cabinet (usually 19’’) to install instrumentation and computers.

RADIUS: Remote Authentication Dial-in User Server.

RAM: Random Access Memory.

Rancher: Complete open source container management multiplatform: https://rancher.com/rancher

RBAC: Role Based Access Control.

RCS: Revision Control System by GNU (obsolete).

Redmine: Service and project management free and open source software tool written in Rubi on rails (GPL license).

Request Tracker (RT): Service management free and open source software tool developed in Perl and distributed under a GPL license.

RGA: Residual Gas Analyzer: mass spectrometer.

ROI or RoI: (detectors) Region of Interest; (financial) Return of Investment.

RPM: Redhat Package Manager.

RPC: Remote Procedure Call.

RS-232, RS-422 (differential), RS485 (multipoint support)… RS stands for Recommended Standard. RS-232 was introduced in the 1960 as protocols to interconnect DTEs (Data Terminal Equipment) with DCEs (Data Communication Equipment).

SaaS: Software as a Service.

SAML: Security Assertion Markup Language.

SAN: Storage Area Network.

SAP: *Systeme, Anwendungen und Produkte in der Datenverarbeitung* . German multinational marked leader in ERP software.

SARDANA. Scientific SCADA based on TANGO optimized for the macro execution and harmonized access to the hardware: https://sardana-controls.org

SAXS: Small Angle Scattering.

SCADA. Supervisory Control And Data Acquisition.

SCAN: Standard procedure for data acquisition in a beamline.

SCCS. Source Code Control System (obsolete).

Sensitivity: Measure of the response of the detector to changes in the input signal.

Scrum: Agile methodology for software development and project management in general.

SDD: Silicon Drift Detector. Type of detectors capable of energy discrimination and widely used in spectroscopy.

Septum: Dipolar magnet often used for injection/extraction in a particle accelerator.

Shibboleth: Open source implementation of a federated authentication infrastructure.

Shutter: Device used to stop or allow beam to the sample or detector. They can be used for safety reasons, personnel or instrument protection or for the synchronization of the experiment.

SIL: Safety Integrity Level. Functional safety level as defined in the Norm IEC 68501 for electrical and electronic components of personnel safety systems.

Single-Sign-On: Unified authentication.

SKA: Square Kilometer Array (https://www.skatelescope.org).

SLA. Service Level Agreement.

SLS. Swiss Light Source. Villigen. Switzerland: http://sls.web.psi.ch

Soleil. Synchrotron nearby Paris, France. http://www.synchrotron-soleil.fr

SPEC: Commercial software for control and data acquisition (www.certif.com).

Spin-Off: Start-up company usually created in a public institute like a university.

SR: Storage Ring: Circular (actually a polygon where the bending magnets are the vortexes) particle accelerator used in synchrotrons.

SRM. Synchrotron Radiation Monitor.

SSH: Secure shell.

SSL: Secure Sockets Layer.

SVN: Subversion. Software version control system. Apache Software Foundation.

SVD: Singular Value Decomposition:

https://en.wikipedia.org/wiki/Singular_value_decomposition

Switch: Network equipment (OSI level 2).
TACO: Framework to build control systems based in RPC and developed at the ESRF
TANGO: Framework to build control systems developed at the ESRF as the evolution of TACO based on CORBA and turned into an international collaboration: https://www.tango-controls.org/.
TAURUS: Framework to build graphical interfaces in scientific and industrial environments. It is built with Python, Qt: https://taurus-scada.org/.
TCO: Total Cost of Ownership.
TCP/IP. Transmission Control Protocol / Internet Protocol. Standard of network protocols in internet. OSI model layers three and four.
TDB: Temporal Database.
TDC: Time to Digital Converter.
Tokamak: Russian: токамак. Toroidal installation for magnetic plasma confinement, such as ITER.
Trigger: Synchronization signal.
Undulator: Type of insertion device in a Synchrotron or XFEL. The magnets are set with a period allowing constructive interference and a spectral response with characteristic peaks.
Umbrella: Federated authentication system. http://umbrellaid.org
UPS: Uninterrupted Power Supply
USB: Universal Serial Line.
Vent: Increase pressure from vacuum to atmospheric values.
VME: Versa Module Europa Bus. Standard developed in the 80s for the Motorola 68000 series. Still widely used in many large installations like CERN or the ESRF.
Well Capacity: The maximum number of electrons (or holes) allowed in a pixel. Directly related to the dynamic range.
Wi-Fi: standard wireless communication protocol implemented on 2.4 and 5 GHz frequencies based on the "Institute of Electrical and Electronics Engineers (IEEE) norm 802.11.
Wiggler: A type of insertion device with magnets separated in a way that they produce a wide and flat spectral output.
WorldFIP. World Factory Instrumentation Protocol. One of the eight fieldbuses defined in IEC 61158. It https://en.wikipedia.org/wiki/Factory_Instrumentation_Protocol
WWW: World Wide Web.
XBPM: X-Ray Beam Position Monitor. Typically installed in Front-ends or beamline optics.
XEDS: Energy Dispersive X-ray spectroscopy.
XFEL: X-Ray Free Electron Laser. Also called the fourth generation synchrotrons. They have a long linear accelerator and long insertion devices to produce short very intense and coherent pulses: https://en.wikipedia.org/wiki/Free-electron_laser.
XML: Extended Markup Language.
XBPM: X-ray Beam Position Monitors: Detectors with two or four channels to measure the position of X-ray beam